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22

RESEARCH ON DEEP HARDENING TITANIUM ALLOY FOR LARGE AIRFRAME STRUCTURAL MEMBERS

Colt Industries/Crucible Inc
Crucible Materials Research Center

Rockwell International Science Center

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Wright-Patterson Air Force Base, Ohio

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This technical report has been reviewed and is approved for publication.

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Fatigue properties		
Time-Temperature-Transformation Characteristics		

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):
This is the final technical report of a contract to develop a titanium alloy capable of being hardened in section sizes significantly greater than currently available while retaining adequate toughness and tensile ductility. Work was carried out in three successive phases: Phase I in which the hardening potential at the center of a six inch section was defined for sixty alloy compositions; Phase II in which the detailed evaluation of tensile properties and fracture toughness data of aged samples led to development of characteristic alloy trend lines for the ten most promising alloys; and finally, (cont. over)

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Phase III in which three alloys - alloy 334 (10Mo-6Cr-2.5Al), 227 (7Mo-4Cr-2.5Al) and 253 (10Mo-8V-2.5Al) - were scaled up as 500 lb. ingots. After a study of various thermomechanical processes, the three alloys were converted to 6-inch diameter billet, duplex solution annealed and aged, and full mechanical properties evaluated. Transverse center properties of alloy 334 attained contract goals while equivalent properties for the other two alloys were very promising. Generally the alloy represents an advance in state-of-the-art deep hardenable titanium alloys. They show little edge to center variation in properties, in contrast to present commercial and semi-commercial alpha-beta alloys which are characterized by large edge to center difference. This property differential is of particular concern in considering fracture toughness since the effective fracture toughness in a heavy section is only as high as the lowest value occurring in the material.

Throughout the program close attention has been paid not only to mechanical properties but also to corresponding structural features. This has helped greatly in heat treatment design, especially in improving transverse ductility. A regression analysis of all structures studied showed on a semi-quantitative basis that a lenticular coarse alpha morphology results in relatively high toughness-low ductility, while a globular shape is associated with low toughness-high ductility. Other analyses and techniques developed during the program should aid not only future titanium alloy design, but also investigation of deep hardenable alloys in general.

FOREWORD

This report was prepared by the Crucible Materials Research Center, Crucible Inc, a wholly-owned subsidiary of Colt Industries, Pittsburgh, Pennsylvania, and the Rockwell International Science Center, Thousand Oaks, California, under USAF Contract F33615-71-C-1525. The research work was performed under Project No. 7351 "Metallic Materials" - Task No. 735105-50. The work was administered by the Metals and Ceramics Division, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, with J. A. Hall and Dr. M. A. Greenfield (AFML/LLM) as project engineers.

This report covers work conducted during the period from May 1, 1971 to October 15, 1974. The principal program participants were R. F. Malone, Technical Director-Titanium; Dr. F. H. Froes, Staff Metallurgist, and V. C. Petersen, Staff Metallurgist, from the Crucible Materials Research Center, and C. G. Rhodes, Senior Staff Associate; J. C. Chesnutt, Technical Staff, and Dr. J. C. Williams, Group Leader, Physical Metallurgy Group for the Rockwell International Science Center. Others cooperating in the project were: E. J. Dulis, President; Dr. R. C. Buehl, Manager-Vacuum Melt; C. F. Yolton, Staff Metallurgist; J. M. Capenos, Staff Microscopist, and J. J. Hauser, Staff Metallurgist, from the Crucible Materials Research Center.

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TABLE I

Compositions Screened in Phase I

Ti-Mo(Zr)-Al(Sn)	Ti-Mo(V, Zr)-Al (Sn)	Ti-Mo(Cr,Mn,Cb)-Al(Sn)	Ti-Mo-V(Cr,Fe)-Al (Phase Splitting)	Ti-6-2-4-6 Type	Ti-Mo-Al-Si
11Mo-4Al	12V-2.5Al	7Mo-4Cr-2.5Al	** 8Mo-8V-2Fe-3Al	** 6Al-2Sn-4Zr-6Mo	9Mo-2.5Al-0.3 Si
9Mo-4Al	10V-2.5Al	5Mo-2Cr-2.5Al	10Mo-8V-2.5Al	4Al-2Sn-4Zr-6Mo	11Mo-1Al-0.5Si
11Mo-2.5Al	12V-1Al		4Mo-8V-6Cr-2.5Al	3Al-2Sn-4Zr-8Mo	* 11Mo-2.5Al-0.5Si
9Mo-2.5Al	13V-3Zr-2.5Al	7Mo-1Mn-2.5Al	12Mo-6V-1Al	* 6Al-2Sn-4Zr-4Mo-4Cr	
7Mo-2.5Al	9V-3Zr-2.5Al	5Mo-2Mn-2.5Al	*10Mo-4Cr-2.5Al	* 6Al-2Sn-4Zr-2Mo-4Cr-2V	
9Mo-1Al	11V-3Zr-1.5Al-3Sn		*10Mo-6Cr-2.5Al		
7Mo-1Al		8Mo-3Cb-2.5Al	*13Mo-4Cr-2.5Al		
11Mo-1Al	6Mo-6V				
9Mo-7.5Sn	5Mo-5V-2.5Al	*10V-4Cr-2.5Al			
9Mo-3Sn	7Mo-5V-2.5Al	* 4Mo-6V-4Cr-2.5Al			
7Mo-3Sn	5Mo-5V-1Al	* 8Mo-2Cr-7.5Sn			
9Mo-1.5Al-3Sn	7Mo-3V-2.5Al	* 8Mo-2Cr-1.5Al-3Sn			
7Mo-1.5Al-3Sn	8Mo-4V-1Al				
8Mo-4Zr-2.5Al	6Mo-3V-4Zr-2.5Al				
8Mo-2Zr-2.5Al	6Mo-3V-4Zr-7.5Sn				
8Mo-4Zr-7.5Sn	5Mo-5V-1.5Al-3Sn				
8Mo-4Zr-3Sn	4Mo-5V-4Zr-1.5Al-3Sn				
8Mo-4Zr-1.5Al-3Sn					
6Mo-4Zr-1.5Al-3Sn					
* 13Mo-4Al					
* 13Mo-2.5Al					
* 11Mo-4Al-3Sn					

* Additional Phase I Alloys

** Control (Commercial) Alloys.

TABLE II

Alloying Materials Used in Formulating Phase I Alloy Melts

Material	Supplier	Purity (%)	Principal Impurities (%)	
Titanium Sponge (Sodium Reduced)	Phillips Brothers	99.5+	0.09	O
			0.02	Fe
			0.01	C
Molybdenum Granules	General Electric Co.	99.5+	0.05	O
Zirconium Sponge (Reactor Grade)	Carborundum Metals Climax, Inc.	99.5+	0.11	O
			0.09	Fe
			0.02	C
Tin (1/8" dia. x 1/8" long pieces)	National Lead Co.	99.85		
Vanadium	Foote Mineral Co.	99.6+	0.09	O
			0.04	C
			0.10	Fe
Chromium (electrolytic)	Union Carbide Corp. Mining & Metals Div.	99.45	0.04	O
			0.04	C
Manganese (electrolytic)	Union Carbide Corp. Mining & Metals Div.	99.78	0.20	O
			0.01	Fe
Columbium (electrolytic)	General Electric Co.	99.9+	0.009	Fe
			0.008	Ta
Iron (electrolytic)	The Glidden Co. Metals Div.	99.90	0.04	O
Aluminum (Pig)	Kaiser Aluminum & Chemical Corp.	99.997		
Silicon	Union Carbide Corp. Mining & Metals Div.	98.94	0.55	Fe
			0.09	Al

TABLE III

BETA TRANSUS AND FINAL ROLLING TEMPERATURE FOR PHASE I ALLOYS

Alloy[1] Button No.	Composition % (Ti Balance)	Beta Transus (°F)	Final[2] Rolling Temperature (°F)
266	11Mo-4Al	1625	1525
264	9Mo-4Al	1675	1575
220	11Mo-2.5Al	1525	1425
225	9Mo-2.5Al	1600	1500
234	7Mo-2.5Al	1625	1525
250	9Mo-1Al	1550	1450
256	7Mo-1Al	1575	1475
215	9Mo-7.5Sn	1450	1350
239	9Mo-3Sn	1475	1375
228	7Mo-3Sn	1500	1400
261	9Mo-1.5Al-3Sn	1575	1475
217	7Mo-1.5Al-3Sn	1550	1350
223	8Mo-4Zr-2.5Al	1575	1475
248	8Mo-2Zr-2.5Al	1625	1525
230	8Mo-4Zr-7.5Sn	1400	1300
244	8Mo-4Zr-3Sn	1475	1375
214	8Mo-4Zr-1.5Al-3Sn	1525	1425
233	6Mo-4Zr-1.5Al-3Sn	1575	1475
226	12V-2.5Al	1450	1350
252	10V-2.5Al	1450	1350
237	12V-1Al	1375	1275
222	11V-3Zr-2.5Al	1425	1325
260	9V-3Zr-2.5Al	1450	1350
254	11V-3Zr-1.5Al-3Sn	1400	1300
246	5Mo-5V-2.5Al	1525	1425
218	7Mo-5V-2.5Al	1500	1400
257	5Mo-5V-1Al	1500	1400
229	6Mo-3V-4Zr-2.5Al	1525	1425
259	7Mo-3V-2.5Al	1575	1475
231	8Mo-4V-1Al	1425	1325
238	6Mo-3V-4Zr-7.5Sn	1350	1250
247	5Mo-5V-1.5Al-3Sn	1475	1375
219	4Mo-5V-4Zr-1.5Al-3Sn	1500	1400

[1] Alloys were arc melted in random fashion to eliminate systematic changes in composition.

[2] Temperature selected for final hot rolling from 0.130" to 0.040" thick.

cont. next page

TABLE III cont.

BETA TRANSUS AND FINAL ROLLING TEMPERATURE FOR PHASE I ALLOYS

Alloy[1] Button No.	Composition % (Ti Balance)	Beta Transus (°F)	Final[2] Rolling Temperature (°F)
227	7Mo-4Cr-2.5Al	1500	1400
242	5Mo-2Cr-2.5Al	1575	1475
255	7Mo-1Mn-2.5Al	1625	1525
236	5Mo-2Mn-2.5Al	1600	1500
249	8Mo-3Cb-2.5Al	1625	1525
216	8Mo-8V-2Fe-3Al	1375	1275
253	10Mo-8V-2.5Al	1425	1325
232	4Mo-8V-6Cr-2.5Al	1325	1225
241	12Mo-6V-1Al	1350	1250
235	6Mo-4Zr-6Al-2Sn	1725	1625
245	6Mo-4Zr-4Al-2Sn	1675	1575
221	8Mo-4Zr-4Al-2Sn	1625	1525
258	11Mo-1Al	1500	1400
240	6Mo-6V	1350	1250
251	9Mo-2.5Al-0.3Si	1625	1525
243	11Mo-1Al-0.5Si	1500	1400
331	13Mo-4Al	1600	1500
332	13Mo-2.5Al	1540	1440
326	11Mo-4Al-3Sn	1615	1515
323	8Mo-2Cr-7.5Sn	1400	1300
324	8Mo-2Cr-1.5Al-3Sn	1500	1400
341	11Mo-2.5Al-0.5Si	1575	1475
336	10V-4Cr-2.5Al	1360	1260
337	4Mo-6V-4Cr-2.5Al	1410	1310
333	10Mo-4Cr-2.5Al	1470	1370
334	10Mo-6Cr-2.5Al	1420	1320
335	13Mo-4Cr-2.5Al	1425	1325
338	4Mo-4Cr-4Zr-6Al-2Sn	1660	1560
339	2Mo-4V-4Cr-4Zr-6Al-2Sn	1600	1500

[1] Alloys were arc melted in random fashion to eliminate systematic changes in composition.

[2] Temperature selected for final hot rolling from 0.130" to 0.040" thick.

TABLE IV

**SELECTION OF SOLUTION TREATMENT AND AGING CYCLES
FOR
PHASE I - TIME-TEMPERATURE-TRANSFORMATION STUDY**

Alloy No.	Composition, w/o (Ti Balance)	Beta Transus, F	Solution Treatment Parameters: Lowest Temp. for Martensite F	ST for 30% Primary α F	Selected Solution Treatment Temp. F	Selected Solution Treatment Time (hours)	Transformation Parameters: Estimated Molybdenum Equivalent %	Estimated TTT Nose Temp. F	Estimated TTT Nose Time (mins)
ORIGINAL ALLOYS									
266	11Mo-4Al	1625	1625	1575	1575	1	13.6	1125	2
264	9Mo-4Al	1675	1650	1600	1600	1	10.6	1150	0.5
220	11Mo-2.5Al	1525	1500	1475	1475	2	14.5	1100	5
225	9Mo-2.5Al	1600	1575	1575	1575	1	11.5	1100	1
234	7Mo-2.5Al	1625	1600	1550	1525	2	8.6	1100	0.4
250	9Mo-1Al	1550	1500	1500	1475	2	12.4	1050	1
256	7Mo-1Al	1575	1575	1500	1525	2	8.1	1100	0.3
258	11Mo-1Al	1500	1500	1475	1475	2	15.4	1100	5
215	9Mo-7.5Sn	1450	1400	1375	1375	4	18.6	1100	10
239	9Mo-3Sn	1475	1475	1425	1425	4	15.2	1050	5
228	7Mo-3Sn	1500	1500	1475	1475	2	12.3	1100	1
261	9Mo-1.5Al-3Sn	1575	1550	1475	1475	2	1413	1050	5
217	7Mo-1.5Al-3Sn	1550	1550	1475	1475	2	11.4	1100	0.5
223	8Mo-4Zr-2.5Al	1575	1550	1525	1525	2	11.1	1100	0.5
248	8Mo-2Zr-2.5Al	1625	1600	1525	1525	2	10.6	1100	0.5
230	8Mo-4Zr-7.5Sn	1400	None	1325	1325	4	18.2	1050	10
244	8Mo-4Zr-3Sn	1475	1475	1400	1400	4	14.8	1100	5
214	8Mo-4Zr-1.5Al-3Sn	1525	1500	1475	1475	2	13.9	1100	5
233	6Mo-4Zr-1.5Al-3Sn	1525	1550	1525	1575	2	11.0	1050	0.5
226	12V-2.5Al	1450	1450	1375	1375	4	9.8	1100	0.4
252	10V-2.5Al	1450	1450	1400	1375	4	7.9	1125	0.3
237	12V-1Al	1375	1350	1300	1275	4	13.5	1050	2
222	11V-3Zr-2Al	1425	1400	1350	1350	4	9.6	1100	0.4
260	9V-3Zr-2.5Al	1450	1450	1400	1375	4	7.7	1075	0.3
254	11V-3Zr-1.5Al-3Sn	1400	1350	1275	1275	4	12.4	1050	1
240	6Mo-6V	1350	1350	1300	1300	4	14.4	1050	5
246	5Mo-5V-2.5Al	1525	1475	1475	1475	2	10.4	1100	0.4
218	7Mo-5V-2.5Al	1500	1450	1400	1400	4	13.2	1100	2
257	5Mo-5V-1Al	1500	1450	1425	1400	4	11.3	1050	0.5
259	7Mo-3V-2.5Al	1575	1550	1475	1475	2	11.4	1100	0.5
231	8Mo-4V-1Al	1425	1400	1375	1375	4	14.8	1075	5

continued

TABLE IV (continued)

SELECTION OF SOLUTION TREATMENT AND AGING CYCLES
FOR
PHASE I - TIME-TEMPERATURE-TRANSFORMATION STUDY

			Solution Treatment Parameters				Transformation Parameters		
					Selected Solution Treatment		Estimated Molybdenum	Estimated TTT Nose	
Alloy No.	Composition, w/o (Ti Balance)	Beta Transus, F	Lowest Temp. for Martensite F	ST for 30% Primary α F	Temp. F	Time (hours)	Equivalent %	Temp. F	Time (mins)
229	6Mo-3V-4Zr-2.5Al	1525	1475	1450	1450	2	11.8	1100	0.5
238	6Mo-3V-4Zr-7.5Sn	1350	1325	1300	1300	4	18.1	1050	10
247	5Mo-5V-1.5Al-3Sn	1475	1475	1450	1425	4	13.2	1050	2
219	4Mo-5V-4Zr-1.5Al-3Sn	1500	1450	1400	1400	4	12.7	1100	2
227	7Mo-4Cr-2.5Al	1500	None	1450	1450	2	16.1	1100	5
242	5Mo-2Cr-2.5Al	1575	1575	1550	1525	2	9.5	1100	0.4
255	7Mo-1Mn-2.5Al	1625	1600	1525	1525	2	10.8	1100	0.5
236	5Mo-2Mn-2.5Al	1600	1600	1525	1525	2	9.9	1100	0.4
249	8Mo-3Cb-2.5Al	1625	1600	1550	1525	2	11.3	1100	0.5
253	10Mo-8V-2.5Al	1425	None	1350	1350	4	20.5	1025	15
232	4Mo-8V-6Cr-2.5Al	1325	None	1300	1300	4	23.1	1000	15
241	12Mo-6V-1Al	1350	None	1275	1275	4	22.5	1000	15
245	6Mo-4Zr-4Al-2Sn	1675	1675	1600	1600	1	8.8	1150	0.3
221	8Mo-4Zr-3Al-2Sn	1625	1600	1575	1575	1	11.7	1150	0.5
251	9Mo-2.5Al-0.5Si	1625	1600	1500	1500	2	11.5	1100	0.5
243	11Mo-1Al-0.5Si	1500	1500	1475	1475	2	15.4	1100	5
CONTRACT ALLOYS									
216	8Mo-8V-2Fe-3Al	1375	None	1325	1325	4	24.2	1000	15
235	6Al-2Sn-4Zr-6Mo	1725	1675	1675	1675	0.5	7.6	1200	0.3

TABLE V

Selection of Solution Treatment and Aging Cycles
for
Time-Temperature-Transformation Studies
Supplemental Alloys

Alloy No.	Composition, w/o (Ti Balance)	Beta Transus, F	SOLUTION TREATMENT PARAMETERS: Lowest Temp. for Martensite F	S.T. for 30% Primary, F	Selected Solution Treatment Temp F	Selected Solution Treatment Time (Hours)	TRANSFORMATION PARAMETERS: Estimated Molybdenum Equivalent %	Estimated TTT Nose Temp F	Estimated TTT Nose Time (Mins)
323	8Mo-2Cr-7.5Sn	1400	None	1425	1375 1325	4 4	16.8	1060 1060	20 80
324	8Mo-2Cr-1.5Al-3Sn	1500	None	1435	1475 1425	2 4	12.0	1080 1080	15 30
326	11Mo-4Al-3Sn	1615	1600	1475	1585 1535	1 2	9.3	1220 1200	15 30
331	13Mo-4Al	1600	1600	1475	1575 1525	1 2	9.0	1125 1115	10 30
332	13Mo-2.5Al	1540	1500	1400	1515 1465	2 2	10.5	1100 1040	10 25
333	10Mo-4Cr-2.5Al	1470	None	1390	1450 1400	2 4	13.9	1010 1010	30 45
334	10Mo-7Cr-2.5Al	1420	None	1275	1400 1350	4 4	17.1	1020 970	45 60
335	13Mo-4Cr-2.5Al	1425	None	1300	1400 1350	4 4	16.9	950 950	45 60
336	10V-4Cr-2.5Al	1360	None	1290	1325 1275	4 4	11.9	900 950	15 30
337	4Mo-6V-4Cr-2.5Al	1410	None	1325	1375 1325	4 4	12.7	1000 975	15 30
338	6Al-2Sn-4Zr-4Mo-4Cr	1660	1660	1580	1625 1575	1 1	6.9	1350 1320	5 18
339	6Al-2Sn-4Zr-2Mo-4V-4Cr	1600	1575	1500	1575 1525	1 2	8.1	1250 1250	10 24
341	11Mo-2.5Al-0.5Si	1575	1575	1480	1550 1500	2 2	8.5	1150 1150	5 10

TABLE VI

Electron Probe Partition Data for 9Mo-2½Al Containing 30% Primary Alpha Phase

	Mo	Al
Wt. % in Beta Phase	13%	1.5%
Wt. % in Alpha Phase*	<1%	4.8%

* Based on mass balance equation after estimation of fraction of alpha phase (30%).

TABLE VII

CALCULATED VALUES FOR NOSE TEMPERATURE AND TIME FOR THE ADDITIONAL PHASE I ALLOYS

		Calculated Values*		
Alloy No.	Composition, w/o Titanium Balance	Beta Transus (F)	Nose Temperature (F)	Nose Time (Sec)
331	13Mo-4Al	1600	1124	24
332	13Mo-2.5Al	1540	1043	23
326	11Mo-4Al-3Sn	1615	1217	17
323	8Mo-2Cr-7.5Sn	1400	1066	21
324	8Mo-2Cr-1.5Al-3Sn	1500	1082	17
341	11Mo-2.5Al-0.5Si	1575	1151	10
336	10V-4Cr-2.5Al	1360	952	28
337	4Mo-6V-4Cr-2.5Al	1410	974	31
333	10Mo-4Cr-2.5Al	1470	1011	37
334	10Mo-6Cr-2.5Al	1420	966	50
335	13Mo-4Cr-2.5Al	1425	954	50
338	4Mo-4Cr-4Zr-6Al-2Sn	1660	1319	18
339	2Mo-4V-4Cr-4Zr-6Al-2Sn	1600	1258	24

* Calculated using the multiple linear regression equations shown in Appendix C.

TABLE VIII

Transformation Characteristics of Initial Phase I Alloys

Alloy No.	Composition, % (Ti Balance)	Beta Transus, F	Solution Treatment Temp F	Solution Treatment Time, Hrs.	Experimental TTT Temp F	Experimental TTT Time (Secs)	ΔT* (^oF)	Estimated TTT Temp F	Estimated TTT Time (Secs)
266	11Mo-4Al	1625	1575	1	1150	13	475	1125	120
264	9Mo-4Al	1675	1600	1	1175	6	500	1150	30
220	11Mo-2.5Al	1525	1475	2	1050	7	475	1100	300
225	9Mo-2.5Al	1600	1575	1	1125	6	475	1100	60
234	7Mo-2.5Al	1625	1525	2	1150	6	475	1100	24
250	9Mo-1Al	1550	1475	2	875	6	675	1050	60
256	7Mo-1Al	1575	1525	2	1150	6	425	1100	18
258	11Mo-1Al	1500	1475	2	1100	7	400	1100	300
215	9Mo-7.5Sn	1450	1375	4	1025	12	425	1100	600
239	9Mo-3Sn	1475	1425	4	975	6	500	1050	300
228	7Mo-3Sn	1500	1475	2	1200	6	300	1100	60
261	9Mo-1.5Al-3Sn	1575	1475	2	975	7	600	1050	300
217	7Mo-1.5Al-3Sn	1550	1475	2	1150	6	400	1100	30
223	8Mo-4Zr-2.5Al	1575	1525	2	1175	6	400	1100	30
248	8Mo-2Zr-2.5Al	1625	1525	2	1150	6	475	1100	30
230	8Mo-4Zr-7.5Sn	1400	1325	4	1025	7	375	1050	600
244	8Mo-4Zr-3Sn	1475	1400	4	1050	6	425	1100	300
214	8Mo-4Zr-1.5Al-3Sn	1525	1475	2	1075	6	450	1100	300
233	6Mo-4Zr-1.5Al-3Sn	1525	1575	2	1200	6	375	1050	30
226	12V-2.5Al	1450	1375	4	1075	6	375	1100	24
252	10V-2.5Al	1450	1375	4	1075	6	375	1125	18
237	12V-1Al	1375	1275	4	800	6	575	1050	2
222	11V-3Zr-2Al	1425	1350	4	1075	6	350	1100	24
260	9V-3Zr-2.5Al	1450	1375	4	1025	6	425	1075	18
254	11V-3Zr-1.5Al-3Sn	1400	1275	4	925	6	475	1050	1

(Continued next page)

TABLE VIII (continued)

Transformation Characteristics of Initial Phase I Alloys

Alloy No.	Composition, % (Ti Balance)	Beta Transus, F	Solution Treatment Temp F	Solution Treatment Time, Hrs.	Experimental TTT Temp F	Experimental TTT Time (Secs)	ΔT* (^oF)	Estimated TTT Temp F	Estimated TTT Time (Secs)
240	6Mo-6V	1350	1300	4	875	9	475	1050	300
246	5Mo-5V-2.5Al	1525	1475	2	1100	6	425	1100	24
218	7Mo-5V-2.5Al	1500	1400	4	1025	6	475	1100	120
257	5Mo-5V-1Al	1500	1400	4	950	6	550	1050	30
259	7Mo-3V-2.5Al	1575	1475	2	1050	6	525	1100	30
231	8Mo-4V-1Al	1425	1375	4	925	6	500	1075	300
229	6Mo-3V-4Zr-2.5Al	1525	1450	2	1100	6	425	1100	30
238	6Mo-3V-4Zr-7.5Sn	1350	1300	4	950	13	400	1050	600
247	5Mo-5V-1.5Al-3Sn	1475	1425	4	1075	6	400	1050	120
219	4Mo-5V-4Zr-1.5Al-3Sn	1500	1400	4	1075	6	425	1100	120
227	7Mo-4Cr-2.5Al	1500	1450	2	1050	9	450	1100	300
242	5Mo-2Cr-2.5Al	1575	1525	2	1100	6	475	1100	24
255	7Mo-1Mn-2.5Al	1625	1525	2	1075	6	550	1100	30
236	5Mo-2Mn-2.5Al	1600	1525	2	1050	6	550	1100	24
249	8Mo-3Cb-2.5Al	1625	1525	2	1125	6	500	1100	30
253	10Mo-8V-2.5Al	1425	1350	4	975	32	450	1025	900
232	4Mo-8V-6Co-2.5Al	1325	1300	4	900	60	425	1000	900
241	12Mo-6V-1Al	1350	1275	4	875	60	475	1000	900
245	6Mo-4Zr-4Al-2Sn	1675	1600	1	1200	6	475	1150	18
221	8Mo-4Zr-3Al-2Sn	1625	1575	1	1300	6	325	1150	30
251	9Mo-2.5Al-0.5Si	1625	1500	2	1150	6	475	1100	30
243	11Mo-1Al-0.551	1500	1475	2	1050	8	450	1100	300
216	8Mo-8V-2Fe-3Al	1375	1325	4	875	150	500	1000	900
235	6Al-2Sn-4Zr-6Mo	1725	1675	0.5	1175	6	550	1200	18

* $\Delta T = B_{tr} - T_N$, B_{tr} is beta transus , T_N is nose temperature.

TABLE IX

Transformation Characteristics of the Additional Phase I Alloys

Alloy No.	Composition, W/O (Ti Balance)	Beta Transus, F	Solution Treatment Temp F	Solution Treatment Time, Hrs.	Experimental TTT Temp F	Experimental TTT Time (Secs)	ΔT^* (°F)	Calculated TTT Nose Temp F	Calculated TTT Nose Time (Secs)
323	8Mo-2Cr-7.5Sn	1400	1375 1325	4 4	1025 1025	66 360	425 425	1066	21
324	8Mo-2Cr-1.5Al-3Sn	1500	1475 1425	2 4	1050 1050	18 28	450 450	1082	17
326	11Mo-4Al-3Sn	1575	1585 1535	1 2	1200 1175	21 32	415 440	1217	17
331	13Mo-4Al	1550	1575 1525	1 2	1175 1100	8 24	425 500	1124	24
332	13Mo-2.5Al	1500	1515 1465	2 2	1150 1025	21 26	400 525	1043	23
333	10Mo-4Cr-2.5Al	1450	1450 1400	2 4	975 975	120 190	500 500	1011	37
334	10Mo-6Cr-2.5Al	1375	1400 1350	4 4	1025 950	165 360	395 470	966	50
335	13Mo-4Cr-2.5Al	1430	1400 1350	4 4	925 1000	225 360	505 430	954	50
336	10 V-4Cr-2.5Al	1375	1325 1275	4 4	825 850	15 24	535 510	952	28
337	4Mo-6V-4Cr-2.5Al	1410	1375 1325	4 4	1025 975	34 190	385 435	974	31
338	4Mo-4Cr-4Zr-6Al-2Sn	1675	1625 1575	1 1	1200 1200	7 17	460 460	1319	18
339	2Mo-4V-4Cr-4Zr-6Al-2Sn	1525	1575 1525	1 2	1150 1150	94 130	450 450	1258	24
341	11Mo-2.5Al-0.5Si	1550	1550 1500	2 2	1200 1200	9 12	375 375	1151	10

$^*\Delta T = B_{tr} - T_n$, where B_{tr} is beta transus and T_n is nose temperature.

TABLE X

AGED STRENGTH AND HARDNESS POTENTIAL FOR THE INITIAL PHASE I ALLOYS

Alloy No.	Composition w/o (Ti Balance)	Beta Transus (°F)	Heat Treatment: Solution Treatment Temp. (°F)	Heat Treatment: Solution Treatment Time (hr)	Heat Treatment: Aging Temp (°F) (8 hr at Temp)	Tensile Properties: Ultimate Tensile Strength (ksi)	Tensile Properties: Yield Strength 0.2% Offset (ksi)	Tensile Properties: Elong. in 0.5" (%)	Tensile Properties: Redn. in Area (%)	Tensile Properties: E ($x10^{-6}$ psi)	Hardness: Heat Treatment As For Tensile Properties (VPN)	Hardness: Increase Over S.T. Hardness (VPN)	Hardness: Est. Max. Hardness at Same Temp. (VPN)	Hardness: Increase Over S.T. Hardness (VPN)	Hardness: Est. Time for Max. Hardness (hrs)	T-T-T Nose Temp. (°F)	T-T-T Nose Time (secs)	ΔT(°F)[a]
266	11Mo-4Al	1625	1575	1	1000	---*	---	---	---	---	459	172	459	172	8	1150	13	475
264	9Mo-4Al	1675	1600	1	1050	---	---	---	---	---	463	183	475	195	1.5	1175	< 6	500
220	11Mo-2.5Al	1525	1475	2	900	204.2	200.8	3.0	3.3	14.6	416	169	440	193	0.1	1050	7	475
225	9Mo-2.5Al	1600	1575	1	950	---	---	---	---	---	424	194	435	205	1.5	1125	< 6	475
224	9Mo-4Al	1650	1600	1	1000	---	---	---	---	---	441	184	465	206	0.6	1250?	< 6	400
234	7Mo-2.5Al	1625	1525	2	1000	185.5	183.1	3.8	4.4	15.9	397	154	397	154	8	1150	< 6	475
250	9Mo-1Al	1550	1475	2	850	175.6	165.4	4.0	16.2	15.7	386	146	460	220	0.3	875?	< 6	675
256	7Mo-1Al	1575	1525	2	1000	169.3	166.5	3.5	8.3	15.5	397	150	432	185	0.7	1150	< 6	425
258	11Mo-1Al	1500	1475	2	950	183.4	170.4	4.0	8.8	15.0	379	144	404	169	0.3	1100	7	400
215	9Mo-7.5Sn	1450	1375	4	900	176.2	154.6	4.0	12.8	15.8	369	152	388	171	2	1025	12	425
239	9Mo-3Sn	1475	1425	4	850	180.3	175.0	4.0	5.3	17.2	390	162	425	197	1.5	975	6	500
228	7Mo-3Sn	1500	1475	2	950	169.8	159.8	5.0	11.5	15.1	366	134	366	134	8	1200	< 6	300
261	9Mo-1.5Al-3Sn	1575	1475	2	850	201.5	193.3	2.0	2.0	15.3	416	171	448	203	1.5	975	7	600
217	7Mo-1.5Al-3Sn	1550	1475	2	950	166.7	140.5	8.0	12.7	14.5	363	117	385	139	0.7	1150	< 6	400
223	8Mo-4Zr-2.5Al	1575	1525	2	1000	---	---	---	---	---	428	164	443	179	1.5	1175	< 6	400
248	8Mo-2Zr-2.5Al	1625	1525	2	1000	186.7	175.7	1.8	6.4	16.0	390	144	447	201	0.4	1150	< 6	475
230	8Mo-4Zr-7.5Sn	1400	1325	4	900	153.2	139.8	4.0	11.9	14.1	344	92	395	143	1	1025	7	375
244	8Mo-4Zr-3Sn	1475	1400	4	900	157.3	130.5	4.0	19.8	14.4	344	121	413	190	0.5	1050	< 6	425
214	8Mo-4Zr-1.5Al-3Sn	1525	1475	2	950	---	---	---	---	---	420	182	420	182	8	1075	< 6	450
233	6Mo-4Zr-1.5Al-3Sn	1575	1525	2	950	---	---	---	---	---	412	151	418	157	3	1200?	< 6	375
226	12V-2.5Al	1450	1375	4	950	155.4	148.6	8.0	24.4	15.5	321	68	395	142	0.2	1075	< 6	375
252	10V-2.5Al	1450	1375	4	950	135.7	125.6	13.0	38.2	15.2	289	62	385	158	0.5	1075	< 6	375
237	12V-1Al	1375	1275	4	800	148.6	133.3	4.7	12.0	13.8	316	84	377	145	0.02	800	< 6	575
222	11V-3Zr-2.5Al	1425	1350	4	950	152.2	143.1	9.0	27.0	14.5	311	66	397	152	0.1	1075	< 6	350
260	9V-3Zr-2.5Al	1450	1375	4	900	160.4	147.5	4.5	6.0	14.2	341	104	372	135	1	1025	< 6	425
254	11V-3Zr-1.5Al-3Sn	1400	1275	4	850	154.7	147.3	4.0	18.6	13.2	335	122	409	196	0.8	925	< 6	475
240	6Mo-6V	1350	1300	4	800	190.9	189.5	4.0	3.6	16.1	428	110	443	125	0.2	875	9	475
246	5Mo-5V-2.5Al	1525	1475	2	950	182.7	177.1	4.0	8.6	16.2	393	152	393	152	8	1100	< 6	425
218	7MO-5V-2.5Al	1500	1400	4	900	177.4	161.4	4.0	6.5	14.6	372	145	410	183	0.1	1025	6	475
257	5Mo-5V-1Al	1500	1400	4	800	169.3	152.9	2.0	3.8	16.4	369	129	392	152	0.4	950	< 6	550
259	7Mo-3V-2.5Al	1575	1475	2	950	188.6	167.4	4.0	6.2	16.1	393	158	425	190	1	1050	< 6	525
231	8Mo-4V-1Al	1425	1375	4	800	176.4	174.5	3.5	7.2	16.2	412	172	417	190	2	925	6	500
229	6Mo-3V-4Zr-2.5Al	1525	1450	2	950	182.8	170.3	4.0	10.5	15.5	383	131	402	150	0.5	1100	< 6	425
238	6Mo-3V-4Zr-7.5Sn	1350	1300	4	850	179.5	168.0	4.0	5.2	14.4	359	139	405	185	1	950	13	400
247	5Mo-5V-1.5Al-3Sn	1475	1425	4	950	173.8	163.8	4.0	17.5	15.0	369	138	395	164	0.5	1075	< 6	400
219	4Mo-5V-4Zr-1.5Al-3Sn	1500	1400	4	950	170.9	159.7	8.0	11.4	14.6	359	114	393	148	0.6	1075	< 6	425
227	7Mo-4Cr-2.5Al	1500	1450	2	900	222.9	211.0	3.0	3.3	15.4	437	177	437	177	8	1050	9	450
242	5Mo-2Cr-2.5Al	1575	1525	2	950	182.1	182.0	4.0	10.7	15.6	404	164	415	175	0.5	1100	< 6	475
255	7Mo-1Mn-2.5Al	1625	1525	2	950	---	---	---	---	---	437	191	445	199	2.5	1075	< 6	550
236	5Mo-2Mn-2.5Al	1600	1525	2	950	179.8	178.9	4.0	7.0	17.4	428	159	445	176	0.6	1050	< 6	550
249	8Mo-3Cb-2.5Al	1625	1525	2	950	---	---	---	---	---	404	152	412	160	2	1125	< 6	500
216†	8Mo-8V-2Fe-3Al	1375	1325	4	850	206.3	194.9	3.5	5.6	18.5	397	129	407	139	25	875	150	500
253	10Mo-8V-2.5Al	1425	1350	4	850	182.3	179.6	2.0	6.5	14.3	393	151	417	175	50	975	32	450
232	4Mo-8V-6Cr-2.5Al	1325	1300	4	850	196.8	170.3	4.0	7.6	15.3	408	163	430	185	3	900	60	425
241	12Mo-6V-1Al	1350	1275	4	800	175.9	159.7	4.0	8.9	13.5	350	100	377?	127?	4?	875	60	475
235†	6Mo-4Zr-6Al-2Sn	1725	1675	0.5	1100	---	---	---	---	---	468	188	468	188	8	1175	< 6	550
245	6Mo-4Zr-4Al-2Sn	1675	1600	1	1050	---	---	---	---	---	437	175	445	183	2	1200	< 6	475
221	8Mo-4Zr-3Al-2Sn	1625	1575	1	1050	---	---	---	---	---	437	177	442	182	0.5	1300?	< 6	325
251	9Mo-2.5Al-0.3Si	1625	1500	2	1000	183.0	179.6	3.0	9.1	15.3	412	167	417	172	2	1150	< 6	475
243	11Mo-1Al-0.5Si	1500	1475	2	950	215.2	199.4	4.0	3.7	16.5	401	166	412	177	0.1	1050	8	450

*Failed in grip because of high notch sensitivity.

[a] Where $\Delta T = (\beta_{Tr} - T_N)$, β_{Tr} is beta transus temperature and T_N is nose temperature.

† Control (commercial) alloys)

TABLE XI

SUMMARY OF AGED HARDNESS FOR THE ADDITIONAL PHASE I ALLOYS

Alloy No.	Composition w/o (Ti Balance)	Beta Transus (^{o}F)	Heat Treatment: Solution Treatment Temp. (^{o}F)	Heat Treatment: Solution Treatment Time (hr)	Heat Treatment: Aging-Temp. (^{o}F) (8 hr @ Temp.)	Hardness: 8 Hour At Temp. (VPN)	Hardness: Est. Max. Hardness At Same Temp. (VPN)	Hardness: Est. Time for Max. Hardness (hrs.)
323	8Mo-2Cr-7.5Sn	1400	1375	4	950	333	340	~100
			1325	4	950	351	360	~100
324	8Mo-2Cr-1.5Al-3Sn	1500	1475	2	950	383	390	20
			1425	4	950	370	390	2
326	11Mo-4Al-3Sn	1575	1585	1	1050	383	397	~ 50
			1535	2	1050	397	410	2
331	13Mo-4Al	1550	1575	1	975	387	392	~ 25
			1525	2	975	417	435	2.5
332	13Mo-2.5Al	1500	1515	2	950	373	388	~ 25
			1465	2	950	397	411	3.5
333	10Mo-4Cr-2.5Al	1450	1450	2	900	383	387	~ 50
			1400	4	900	401	405	5
334	10Mo-6Cr-2.5Al	1375	1400	4	850	264	405	~250
			1350	4	850	289	410	~250
335	13Mo-4Cr-2.5Al	1430	1400	4	850	319	385	~100
			1350	4	850	366	404	~ 50
336	10V-4Cr-2.5Al	1375	1325	4	850	390	396	~ 50
			1275	4	850	360	375	6
337	4Mo-6V-4Cr-2.5Al	1410	1375	4	875	421	430	5
			1325	4	875	360	385	~ 50
338	4Mo-4Cr-4Zr-6Al-2Sn	1675	1625	1	1050	464	466	4
			1575	1	1050	464	479	1
339	2Mo-4V-4Cr-4Zr-6Al-2Sn	1525	1575	1	1050	421	424	6
			1525	2	1050	429	429	8
341	11Mo-2.5Al-0.5Si	1550	1550	2	950	425	446	2.5
			1500	2	950	421	430	2

TABLE XII

EFFECT OF COOLING FROM THE ANNEALING TEMPERATURE AT A RATE DESIGNED TO SIMULATE THAT AT THE CENTER OF A 6" DIAMETER SECTION ON SUBSEQUENT ATTAINABLE STRENGTH

Alloy No.	Composition	Beta Transus (°F)	T-T-T Characteristics Nose Temp. (°F)	T-T-T Characteristics Nose Time (Secs)	Heat Treatment: Solution Treatment Temp. (°F)	Solution Treatment Time (Hrs)	Aging Treatment Temp. (°F)	Aging Treatment Time (Hrs)	Cooling Technique	Hardness (VPN)	Loss in Attainable Strength After SC (VPN)
9-2.5 5 lb. melt	9Mo-2.5Al	1600	1125	6	1500	2	-	-	WQ	235	
					"	"	950	8	WQ	394	
					"	"	-	-	SC[a]	281	
					"	"	950	8	SC[a]	345	49
215	9Mo-7.5Sn	1450	1025	12	1375	4	-	-	WQ	236	
					"	"	900	8	WQ	376	
					"	"	-	-	SC[b]	262	
					"	"	900	8	SC[b]	350	26
232	4Mo-8V-6Cr-2.5Al	1325	900	60	1300	4	-	-	WQ	264	
					"	"	850	8	WQ	404	
					"	"	-	-	SC[c]	266	
					"	"	850	8	SC[c]	401	3

SC[a] Simulated cool: 1500F→1300F in 1.9 minutes, 1300F→1100F in further 0.8 minutes, 1100F→900F in further 0.8 minutes and final air cool.

SC[b] Simulated cool: 1375F→1175F in 1.9 minutes, 1175F→975F in further 0.9 minutes, 975F→775F in further 1 minute and final air cool.

SC[c] Simulated cool: 1300F→1100F in 2.0 minutes, 1100F→900F in further 0.9 minutes, 900F→700F in further 1.1 minutes and final air cool.

TABLE XIII

Alloys Selected for Phase II Evaluation

Alloy No.	Composition, W/O Titanium Balance	Beta Transus (F)	Density (lbs/in^3)	Estimated U.T.S. at Center of Six-Inch Section/Density (Inches)
232	4Mo-8V-6Co-2.5Al	1325	0.171	1.18
334	10Mo-6Cr-2.5Al	1420	0.171	1.14
253	10Mo-8V-2.5Al	1425	0.173	1.12
337	4Mo-6V-4Cr-2.5Al	1410	0.168	1.19
227	7Mo-4Cr-2.5Al	1500	0.169	1.22
243	11Mo-1Al-0.5Si	1500	0.172	1.15
261	9Mo-1.5Al-3Sn	1575	0.172	1.11
266	11Mo-4Al	1625	0.169	1.21
339	6Al-2Sn-4Zr-2Mo-4Cr-4V	1600	0.162	1.23
338	6Al-2Sn-4Zr-4Mo-4Cr	1660	0.163	1.22

TABLE XIV

PHASE II
MATERIALS USED IN INGOT FORMULATIONS

Material	Purity, %	Principal Impurities, % O	N	Fe	C
Titanium Sponge, ICI	99.5+	0.09	0.01	-	-
Molybdenum Granules	99.5+	0.05	-	-	-
Zirconium Sponge (Reactor grade)	99.5+	0.11	-	0.09	0.02
Tin, 1/8" dia. x 1/8"	99.85	-	-	-	-
Vanadium/Aluminum Master (85-15)	-	0.210	-	0.4	-
Vanadium	99.6+	0.09	-	0.10	0.04
Chromium (Electrolytic)	99.45	0.04	-	-	0.04
Aluminum	99.997	-	-	-	-
Silicon	98.94	-	-	0.55	-

TABLE XV

PROTECTIVE COATING DETAILS

Forging

Temperature	Metlseel Coating	Thickness
1500-1750F	RA-537	5 - 10 inches
1800-2300F	RA-538	10-20 inches

Hot Rolling

Temperature	Metlseel Coating	Thickness
1200-1700F	RA-536	2 - 4 inches
1500-2100F	RA-537	5 - 10 inches

Supplier: Pemco Products
Glidden-Durkee Division
5601 Eastern Avenue
Baltimore, Md.

TABLE XVI

TEMPERATURES FOR PHASE II FORGING AND ROLLING

Phase II Ingot No.	Alloy Composition	Forging Temperature, F Initial	Reheats	Hot Rolling Temperature, F
149	4Mo-8V-6Cr-2.5Al	1750	1750,1600,1500	1500
177	10Mo-6Cr-2.5Al	1750	1750,1600,1500	1500
170	10Mo-8V-2.5Al	1750	1750,1600,1500	1500
174	4Mo-6V-4Cr-2.5Al	1750	1750,1600,1500	1500
169	7Mo-4Cr-2.5Al	1750	1750,1600,1500	1575
171	11Mo-1Al-0.5Si	1750	1750,1600,1500	1575
168	9Mo-1.5Al-3Sn	1750	1750,1600,1500	1575
167	11Mo-4Al	1750	1750,1600,1500	1650
176	2Mo-4V-4Cr-4Zr-6Al-2Sn	1850	1850,1750,1650	1750
175	4Mo-4Cr-4Zr-6Al-2Sn	1850	1850,1750,1650	1800

TABLE XVII

HEAT TREATMENT CYCLES FOR PHASE II ALLOYS

Simulated Cooling at Center - Six Inch Diameter

Alloy No.	Phase II Ingot No.	Composition	Solution Treatment	Simulated Cooling Cycle	Age Cycle
232	149	4Mo-8V-6Cr-2.5Al	1300F-4 hrs	1100F-118 secs, 900F-58 secs, 700F-62 secs, air cool	850F-8 hrs
334	177	10Mo-6Cr-2.5Al	1325F-4 hrs	1125F-119 secs, 925F-55 secs, 725F-62 secs, air cool	875F-96 hrs
253	170	10Mo-8V-2.5Al	1325F-4 hrs	1125F-119 secs, 925F-55 secs, 725F-62 secs, air cool	900F-96 hrs
337	174	4Mo-6V-4Cr-2.5Al	1350F-4 hrs	1150F-118 secs, 950F-53 secs, 750F-61 Secs, air cool	875F-24 hrs
227	169	7Mo-4Cr-2.5Al	1425F-4 hrs	1225F-116 secs, 1025F-50 secs, 825F-55 secs,air cool	900F-8 hrs
243	171	11Mo-1Al-0.5Si	1450F-2 hrs	1250F-116 secs, 1050F-49 secs, 850F-53 secs,air cool	1000F-4 hrs
261	168	9Mo-1.5Al-3Sn	1475F-2 hrs	1275F-114 secs, 1075F-48 secs, 875F-51 secs,air cool	900F-4 hrs
266	167	11Mo-4Al	1515F-1 hr	1375F-112 secs, 1175F-43 secs, 975F-43 secs,air cool	1000F-8 hrs
339	176	2Mo-4V-4Cr-4Zr-6Al-2Sn	1475F-2 hrs	1275F-114 secs, 1075F-48 secs, 875F-51 secs,air cool	1050F-24 hrs
338	175	4Mo-4Cr-4Zr-6Al-2Sn	1550F-2 hrs	1350F-112 secs, 1150F-43 secs, 950F-46 secs,air cool	1050F-4 hrs
Control Alloys					
216	172	8Mo-8V-2Fe-3Al	1300F-4 hrs	1100F-118 secs, 900F-58 secs, 700F-62 secs, air cool	900F-96 hrs
235	178	6Al-2Sn-4Zr-6Mo	1515-6 hrs	1315F-112 secs, 1175F-43 secs, 975F-43 secs,air cool	1100F-8 hrs

TABLE XVIII

SOLUTION TREATMENT AND AGING CYCLES FOR PHASE II ALLOYS

Alloy No.	Phase II Ingot No.	Composition	Beta Trans. °F	Solution Temp. Range	Aging Treatment Range
232	149	4Mo-8V-6Cr-2.5Al	1325	1250-1350F	850 - 1000 F 8 hrs.
334	177	10Mo-6Cr-2.5Al	1375	1275-1325F	875 - 975 F 96 hrs.
253	170	10Mo-8V-2.5Al	1425	1300-1450F	850 - 1100 F 4-96 hrs.
337	174	4Mo-6V-4Cr-2.5Al	1410	1250-1350F	875 - 975 F 24 hrs.
227	169	7Mo-4Cr-2.5Al	1500	1400-1475F	900 - 1100 F 8 hrs.
243	171	11Mo-1Al-0.5Si	1500	1425-1475F	950 - 1000 F 4-8 hrs.
261	168	9Mo-1.5Al-3Sn	1575	1450-1475F	850 - 900 F 4-8 hrs.
266	167	11Mo-4Al	1625	1500-1575F	1000 - 1050 F 8 hrs.
339	176	2Mo-4V-4Cr-4Zr-6Al-2Sn	1525	1325-1475F	1050 F - 24 hrs.
338	175	4Mo-4Cr-4Zr-6Al-2Sn	1675	1500-1550F	1050 - 1250 F 4 hrs.

TABLE XIX

PHASE II EVALUATION PROGRAM

Alloy No.	Phase II Ingot No.	Composition	Mechanical Property Study	Dynamic Modulus	Chem. Comp.	Density	Structural Character-ization	Fine Structure Study	Fracture Crack Path Investigation
232	149	4Mo-8V-6Cr-2.5Al	X	X	X	X	-	X	-
334	177	10Mo-6Cr-2.5Al	X	-	X	-	X	-	X
253	170	10Mo-8V-2.5Al	X	X	X	X	-	X	-
337	174	4Mo-6V-4Cr-2.5Al	X	-	X	-	X	-	-
227	169	7Mo-4Cr-2.5Al	X	X	X	X	X	X	X
243	171	11Mo-1Al-0.5Si	X	-	X	-	-	X	-
261	168	9Mo-1.5Al-3Sn	X	X	X	X	X	X	-
266	167	11Mo-4Al	X	X	X	X	-	X	-
339	176	2Mo-4V-4Cr-4Zr-6Al-2Sn	X	-	X	-	-	-	-
338	175	4Mo-4Cr-4Zr-6Al-2Sn	X	-	X	-	-	-	-
Control Alloys									
216	172	8Mo-8V-2Fe-3Al	X	-	X	X	X	-	X
235	178	6Al-2Sn-4Zr-6Mo	X	-	X	-	X	-	X

TABLE XX

PHASE II AGED MECHANICAL PROPERTY DATA
WATER QUENCHED VS. SIMULATED COOLED CONDITIONS

Phase I No.	Phase II No.	Composition (bal. Ti)	Density (lbs/in³)	Solution Treatment (F°)	Cooling Path	Hardness As Cooled (VPN)	Aging Treatment (F°)	Speci. Dir.	Aged Tensile Properties: Ultimate Tensile Strength (ksi)	Yield Strength 0.2% Offset (ksi)	Elong. in 4D (%)	Redn. of Area (%)	E(x10⁶ psi)	Break	Aged Hardness (VPN)	Fracture Toughness (ksi/in.)
266	167	11Mo-4Al	0.169	1575-1 hr	WQ	248	1000-8 hr	T	208.6	*	1.0	4.0	17.2	C	404	26,27.6,25.5
								L	193.8	*	<1.0	4.2	16.2	C		44.3
					SC	301		T	192.4	181.6	3.0	6.0	16.7	A	379	38.9,33.3
								L	170.5	160.5	<1.0	5.2	15.6	B		42.5
				1550-2 hr	WQ	289		-	--	--	--	--	--	-@	401	N.D.
					SC	306		T	192.4	185.4	1.0	5.2	17.6	C	376	43.2,48.5
								L	169.4	156.5	2.0	4.4	16.2	B		N.D.
261	168	9Mo-1.5Al-3Sn	0.172	1475-2 hr	WQ	236	900-4 hr	T	200.8	200.8	--	--	14.3	OGM	412	†
								T	177.1	*	--	--	14.8	OGM		
								L	223.0	206.0	<1.0	4.2	14.6	C		†
					SC	292		T	202.0	176.0	6.0	27.8	17.2	B	393	†
								L	202.0	179.0	3.0	7.8	14.9	B		†
				1450-2 hr	WQ	256		-	--	--	--	--	--	-@	397	N.D.
					SC	283		T	181.2	166.7	10.0	46.1	14.4	C	369	6.5,15.7
								L	176.6	159.5	8.0	37.3	14.0	C		N.D.
232	149	4Mo-8V-6Cr-2.5Al	0.171	1350-4 hr	WQ	-	850-8 hr	-	--	--	--	--	--	-	-	--Δ
				1300-4 hr	WQ	272		T	207.7	199.0	3.0	6.8	15.2	B	390	36.2,28.1
								L	203.4	197.1	3.0	9.4	14.9	C		30.0
					SC	264		T	208.8	200.8	<1.0	8.6	16.0	C	393	33.0,28.6,25.9
								L	212.4	193.6	3.0	8.6	15.3	C		31.1
				1275-4 hr	WQ	278		-	--	--	--	--	--	-@	386	N.D.
					SC	283		T	193.6	185.1	2.0	8.2	16.3	B	383	36.9,36.2
								L	194.7	186.2	4.0	6.3	16.6	A		N.D.
253	170	10Mo-8V-2.5Al	0.171	1450-2 hr	WQ	-	850	-	--	--	--	--	--	-	-	--Δ
				1325-4 hr	WQ	256	900-96 hr	T	199.8	194.8	3.0	9.4	16.4	C	372	42.0,42.2,39.4
								L	184.8	183.0	1.0	3.2	15.4	B		38.0
					SC	256		T	203.2	195.3	3.0	2.4	16.3	A	376	40.1,41.7
								L	183.4	180.0	<1.0	3.2	13.2	A		36.6
				1300-4 hr	WQ	262		-	--	--	--	--	--	-@	366	N.D.
					SC	274		T	189.2	185.0	4.0	7.5	15.9	C	366	47.5,45.6
								L	181.0	173.1	2.0	6.4	17.2	C		N.D.
243	171	11Mo-1Al-0.5Si	0.172	1475-2 hr	WQ	-	950	-	--	--	--	--	--	-	-	--Δ
							1000	-	--	--	--	--	--	-	-	--Δ
				1450-2 hr	WQ	226	1000-4 hr	T	188.0	--	--	--	16.1	OGM	376	21.2 †
								L	173.2	162.3	1.0	3.2	16.5	C		†
					SC	314		T	187.0	177.1	2.0	4.2	15.7	C	353	23.2,24.5
								L	164.6	144.0	2.0	6.6	13.5	C		22.8
				1425-4 hr	WQ	-	950	-	--	--	--	--	--	-	-	--Δ
227	169	7Mo-4Cr-2.5Al	0.169	1475-2 hr	WQ	-	900	-	--	--	--	--	--	-	-	--Δ
				1450-2 hr	WQ	-		-	--	--	--	--	--	-	-	--Δ
				1425-4 hr	WQ	268	900-8 hr	T	210.9	199.5	2.0	7.9	14.1	A	397	36.3,41.5
								L	204.6	199.9	<1.0	4.2	15.8	B		44.9
					SC	274		T	194.8	184.0	--	--	15.1	OGM	366	36.3,39.8
								L	185.2	166.9	8.0	7.0	16.1	OGM		78.7(fibrous)
				1400-4 hr	WQ	272		-	--	--	--	--	--	-	401	N.D.
					SC	280		T	194.0	176.5	2.0	6.8	15.3	B	379	40.5,39.1
								L	184.0	165.6	4.0	5.8	15.9	C		N.D.
216	172	8Mo-8V-2Fe-3Al	0.172	1300-4 hr	WQ	278	900-96 hr	T	208.4	201.5	4.0	11.6	16.1	C	390	29.7,34.8
								L	202.4	195.5	2.0	5.6	16.2	B		36.5
					SC	280		T	200.4	195.2	6.0	20.1	15.7	B	386	35.5,36.3
								T	197.4	193.6	5.0	18.8	15.9	C		
								L	202.0	194.3	4.0	13.0	16.0	B		87.5(short trans.fibrous)
				1275-4 hr	WQ	283		-	--	--	--	--	--	-@	363	N.D.
					SQ	264		T	188.4	183.5	10.0	26.6	17.0	B	366	43.1,44.7
								L	186.6	181.6	1.0	10.4	17.2	OGM		N.D.

Δ - Not investigated in Phase II.
* - Premature failure.
† - Low fracture toughness, broke during pre-cracking.
@ - Tensile properties not determined.
N.D. - Not determined.

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TABLE XX (Cont'd)

PHASE II AGED MECHANICAL PROPERTY DATA WATER QUENCHED VS. SIMULATED COOLED CONDITIONS

Phase I No.	Phase II No.	Composition (bal. Ti)	Density (lbs/in³)	Solution Treatment (F°)	Cooling Path	Hardness As Cooled (VPN)	Aging Treatment (F°)	Speci. Dir.	Aged Tensile Properties: Ultimate Tensile Strength (ksi)	Yield Strength 0.2% Offset (ksi)	Elong. in 4D (%)	Redn. of Area (%)	E(x10⁶ psi)	Break	Aged Hardness (VPN)	Fracture Toughness (ksi√in.)
334	177	10Mo-6Cr-2.5Al	0.171	1325-4 hr	WQ	272	875-96 hr	T	213.6	206.8	<1.0	4.0	16.7	B	408	36.1,33.5
								L	196.8	194.0	1.0	8.2	15.7	C		55.1
					SC	264		T	188.3	185.9	1.0	4.4	15.0	B	386	41.5,42.3
								T	204.1	197.2	<1.0	2.8	15.1	C		
								L	189.1	184.2	2.0	7.4	15.4	B		69.9
				1275-4 hr	WQ	272		-	--	--	--	--	--	-@	369	N.D.
					SC	266		T	176.9	168.3	3.0	7.0	14.0	A	376	N.D.
								T	178.1	170.7	1.0	9.0	13.8	OGM		
337	174	4Mo-6V-4Cr-2.5Al	0.168	1350-4 hr	WQ	274	875-24 hr	T	212.2	207.1	1.0	6.6	15.5	B	404	37.6,28.3
								L	191.2	189.2	2.0	15.0	15.7	C		33.8
					SC	278		T	201.6	199.2	<1.0	2.8	16.8	A	397	28.5, †
								T	194.4	*	1.0	7.0	17.2	B		
								L	204.4	197.7	3.0	8.6	15.0	A		29.7
				1300-4 hr	WQ	299		-	--	--	--	--	--	-@	379	N.D.
					SC	306		T	187.1	180.7	2.0	7.5	13.9	B	383	N.D.
								T	189.4	184.3	3.0	10.8	15.5	B		
338	175	4Mo-4Cr-4Zr-6Al-2Sn	0.163	1550-2 hr	WQ	321	1050-4 hr	T	241.9	240.7	<1.0	3.4	15.4	B	463	†,†
								L	239.5	231.4	<1.0	6.0	17.2	B		†
					SC	363		T	192.8	189.2	1.0	7.4	17.6	B	404	†,13.5
								T	184.9	*	<1.0	--	18.1	OGM		
								L	186.5	184.8	2.0	5.9	17.8	B		26.6
				1500-2 hr	WQ	347		-	--	--	--	--	--	-@	441	N.D.
					SC	376		T	191.0	186.0	3.0	11.9	15.6	A	401	N.D.
								T	188.1	182.7	1.0	6.3	15.1	B		
339	176	2Mo-4V-4Cr-4Zr-6Al-2Sn	0.162	1475-2 hr	WQ	314	1050-24 hr	T	210.8	*	<1.0	6.0	18.7	C	437	9.6,15.3
								L	219.7	217.4	--	--	16.5	OGM		23.9
					SC	390		T	192.2	191.2	--	--	17.5	OGM	428	22.8,18.2
								T	192.0	190.0	--	--	16.7	OGM		
								T	183.2	*	<1.0	4.0	16.3	C		
								L	194.8	192.3	4.0	12.2	17.2	C		33.8
				1425-4 hr	WQ	344		-	--	--	--	--	--	-@	428	N.D.
					SC	376		T	181.9	181.0	<1.0	7.0	15.1	C	416	N.D.
								T	150.8	*	*	*	15.9	OGM		
235	178	6Al-2Sn-4Zr-6Mo	0.165	1575-1 hr	WQ	330	1100-8 hr	T	184.8	177.0	10.0	20.7	17.3	B	383	28.6,29.3
								L	185.0	175.6	8.0	21.6	16.5	A		34.9
					SC	344		T	169.6	161.8	12.0	27.0	16.9	A	356	35.8,37.3
								T	173.3	164.6	11.0	22.0	17.4	B		
								L	171.8	160.8	12.0	24.6	15.9	B		40.0

Δ -Not investigated in Phase II.
* -Premature failure.
† -Low fracture toughness, broke during pre-cracking.
@ -Tensile properties not determined.
N.D.-Not determined.

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TABLE XXI

PHASE II AGED MECHANICAL PROPERTY DATA WATER QUENCHED SAMPLES

Phase I No.	Phase II No.	Composition (bal. Ti)	Density (lbs/in³)	Solution Treatment (F°)	Hardness As Quenched (VPN)	Aging Treatment (F°)	Speci. Dir.	Aged Tensile Properties: Ultimate Tensile Strength (ksi)	Yield Strength 0.2% Offset (ksi)	Elong. in 4D (%)	Redn. of Area (%)	$E(x10^6$ psi)	Break	Aged Hardness (VPN)	Fracture Toughness (ksi/in.)
266	167	11Mo-4Al	0.169	1575-1 hr	248	1000-8 hr	T	208.6	*	1.0	4.0	17.2	C	404	26,27.6,25.5
							L	193.8	*	<1.0	4.2	16.2	C		44.3(Short Trans.Fibrous)
				1550-2 hr	289	1000-8 hr	-	--	--	--	--	--	-@	401	ND
				1500-2 hr		1050-8 hr	T	187.4	180.4	3.0	7.2	16.7	C		ND - Y
							T	179.4	172.8	1.0	1.8	15.7	C		
261	168	9Mo-1.5Al-3Sn	0.172	1475-2 hr	245	850-8 hr	L	201.5	193.3	2.0	2.0	15.3	B	416	ND
					.236	900-4 hr	T	200.8	200.8	--	--	14.3	OCM	412	†
							T	177.1	*	--	--	14.8	OCM		
							L	223.0	206.0	<1.0	4.2	14.6	C		†
				1450-2 hr	256	900-4 hr	-	--	--	--	--	--	-@	397	ND
232	149	4Mo-8V-6Cr-2.5Al	0.171	1300-4 hr	272	850-8 hr	T	207.7	199.0	3.0	6.8	15.2	B	390	36.2,28.1
							L	203.4	197.1	3.0	9.4	14.9	C		30.0
					245		L	196.8	170.3	4.0	7.6	15.3	B	408	ND - Y
				1275-4 hr	278	850-8 hr	-	--	--	--	--	--	-@	386	ND
				1275-4 hr		1000-8 hr	L	142.0	138.4	10.0	23.2	16.3	B		ND - X
							L	152.5	147.5	8.0	36.1	15.5	C		X
				1250-4 hr		950-8 hr	L	159.7	154.8	12.0	27.4	14.9	C		ND - X
							L	149.2	144.1	8.0	32.8	14.3	C		X
253	170	10Mo-8V-2.5Al	0.171	1375-4 hr		1000-4 hr	L	147.0	122.6	10.0	38.0	11.0	C		ND - X
							L	147.7	130.0	6.0	27.9	12.0	C		X
						1000-8 hr	L	164.5	148.9	6.0	17.0	14.5	C		ND - X
							L	153.5	140.0	8.0	31.0	14.7	A		X
						1100-4 hr	L	132.7	123.9	4.0	28.5	14.9	C		ND - X
							L	143.8	129.6	8.0	27.1	11.7	C		X
				1350-4 hr	242	850-8 hr	L	182.3	179.6	2.0	6.5	14.3	B	393	ND - Y
				1325-4 hr	256	900-96 hr	T	199.8	194.8	3.0	9.4	16.4	C	372	42.0,42.2,39.4
							L	184.8	183.0	1.0	3.2	15.4	B		38.0
				1300-4 hr	262		-	--	--	--	--	--	-@	366	ND
						975-96 hr	L	161.3	154.8	10.0	11.6	16.4	C		ND
							L	158.8	151.5	14.0	23.8	15.5	B		
243	171	11Mo-1Al-0.5Si	0.172	1475-2 hr	235	950-8 hr	L	215.2	199.4	4.0	3.7	16.5	B	401	ND - Y
				1450-2 hr	226	1000-4 hr	T	188.0	--	--	--	16.1	OCM	376	21.2 †
								173.2	162.3	1.0	3.2	16.5	C		†
227	169	7Mo-4Cr-2.5Al	0.169	1450-2 hr	260	900-8 hr	L	222.9	211.0	3.0	3.3	15.4	B	437	ND - Y
						1000-8 hr	L	172.0	161.7	8.0	23.0	--	C		X
							L	176.9	167.0	10.0	23.0	--	C		X
						1100-8 hr	L	146.5	141.6	12.0	31.7	14.6	C		X
							L	149.7	144.8	12.0	27.0	--	C		X
				1425-4 hr	268	900-8 hr	T	210.9	199.5	2.0	7.9	14.1	A	397	36.3,41.5
							L	204.6	199.9	<1.0	4.2	15.8	B		44.9
						1000-8 hr	-	--	158 •	--	--	--	-		59.4,70.0
				1400-4 hr	272	900-8 hr	-	--	--	--	--	--	-	401	ND
334	177	10Mo-6Cr-2.5Al	0.171	1325-4 hr	272	875-96 hr	T	213.6	206.8	<1.0	4.0	16.7	B	408	36.1,33.5
							L	196.8	194.0	1.0	8.2	15.7	C		55.1
							L	187.3	*	2.0	--	17.3	B		Y
							L	185.9	*	--	--	16.0	OCM		Y
						950-96 hr	L	160.6	157.4	8.0	7.0	16.3	A		76.8,68.2
							L	157.6	153.6	13.0	33.2	16.0	A		
						975-96 hr	L	164.7	152.6	16.0	32.8	15.8	C		Y
							L	168.0	155.8	12.0	20.8	16.3	A		Y
				1300-4 hr		925-96 hr	L	179.0	170.5	6.0	14.5	16.6	C		
							L	178.9	168.3	8.0	14.1	16.3	B		
				1275-4 hr	272	875-96 hr	-	--	--	--	--	--	@		ND
						975-96 hr	L	154.7	147.6	12.0	22.9	15.1	A		Y
							L	157.6	150.0	12.0	19.4	16.0	B		Y

TABLE XXI (Cont'd)

PHASE II AGED MECHANICAL PROPERTY DATA WATER QUENCHED SAMPLES

Phase I No.	Phase II No.	Composition (bal. Ti)	Density (lbs/in^3)	Solution Treatment (F°)	Hardness As Quenched (VPN)	Aging Treatment (F°)	Speci. Dir.	Aged Tensile Properties: Ultimate Tensile Strength (ksi)	Yield Strength 0.2% Offset (ksi)	Elong. in 4D (%)	Rcdn. of Area (%)	E(x10^6 psi)	Break	Aged Hardness (VPN)	Fracture Toughness (ksi/in.)
337	174	4Mo-6V-4Cr-2.5Al	0.168	1350-4 hr	274	875-24 hr	T	212.2	207.1	1.0	6.6	15.5	B	404	28.3
							L	191.2	189.2	2.0	15.0	15.7	C		33.8
							L	204.0	196.0	6.0	10.5	15.5	A		Y
							L	204.5	197.7	2.0	10.6	14.8	A		Y
						975-24 hr	-	--	158.5 •	--	--	--	-		49.4,49.0
				1300-4 hr	299	875-24 hr	-	--	--	--	--	--	@	379	ND
				1300-4 hr		975-24 hr	L	151.6	147.7	10.0	31.0	15.4	A		Y
							L	154.1	149.2	14.0	34.0	15.7	A		Y
				1250-4 hr		875-24 hr	L	165.7	161.0	6.0	13.0	15.1	B		Y
							L	166.5	161.5	6.0	23.0	15.0	B		Y
						975-24 hr	L	145.1	141.2	12.0	23.5	15.5	A		Y
							L	142.1	136.8	8.0	28.0	15.7	B		Y
338	175	4Mo-4Cr-4Zr-6Al-2Sn	0.163	1550-2 hr	321	1050-4 hr	T	241.9	240.7	<1.0	3.4	15.4	B	463	†,†
							L	239.5	231.4	<1.0	6.0	17.2	B		†
				1500-2 hr	347	1050-4 hr	-	--	--	--	--	--	@	441	ND
						1150-4 hr	L	197.5	188.1	8.0	16.9	15.4	C		Y
							L	192.3	185.5	6.0	13.3	15.6	C		Y
						1250-4 hr	L	185.5	182.4	7.0	4.6	16.2	C		22.1,32.3
							L	188.2	180.0	8.0	9.6	17.0	C		
339	176	2Mo-4V-4Cr-4Zr-6Al-2Sn	0.162	1475-2 hr	314	1050-24 hr	T	210.8	*	<1.0	6.0	18.7	C	437	9.6,15.3
							L	219.7	217.4	--	--	16.5	OGM		23.9
				1425-4 hr	344	1050-24 hr	-	--	--	--	--	--	@	428	ND
				1375-4 hr		1050-24 hr	L	179.0	169.4	6.0	0.2	14.7	C		Y
							L	165.7	160.0	4.0	0.7	14.8	A		Y
				1325-4 hr		1050-24 hr	L	198.5	198.3	3.0	2.8	17.2	C		21.4,22.4
							L	203.0	200.4	4.0	3.0	16.8	A		
235	178	6Al-2Sn-4Zr-6Mo	0.165	1575-1 hr	330	1100-8 hr	T	184.8	177.0	10.0	20.7	17.3	B	383	28.6,29.3
							L	185.0	175.6	8.0	21.6	16.5	A		34.9

Determined by slow bend of pre-cracked Charpy samples.
* Premature failure.
† Low fracture toughness, broke during pre-cracking.
@ Tensile properties not determined.
ND Not determined.
X Microtensiles from Phase II plate rolled to 0.045" sheet.
Y Microtensiles from Phase I sheet.
• Estimated.
OGM Outside gage mark

TABLE XXII

AGED DYNAMIC MODULUS MEASUREMENTS OF SELECTED ALLOYS

Alloy	Composition (bal.Ti)	Direction[a]	Dynamic Modulus, E ($lb.in.^{-2}$)
227	7Mo-4Cr-2.5Al	L	14.8×10^6
		T	15.2
232	4Mo-8V-6Cr-2.5Al	L	12.9
		T	14.3
240	6Mo-6V	L	15.1
		T	16.5
253	10Mo-8V-2.5Al	L	14.0
		T	14.8
261	9Mo-1.5Al-3Sn	L	14.8
		T	16.3
266	11Mo-4Al	L	14.4
		T	15.6

[a] L - longitudinal
T - transverse

TABLE XXIII

CHEMICAL ANALYSIS OF PHASE II ALLOYS

Alloy No.	Phase II Ingot No.	Nominal Composition (bal. Ti)	Chemical Analysis (w/o)[a]								
			Mo	Cr	Al[b]	V	Zr	Sn	Si	Fe	O_2[c]
266	167	11Mo-4Al	11.20	-	4.20	-	-	-	-	-	0.112
261	168	9Mo-1.5Al-3Sn	9.20	-	1.80	-	-	3.72	-	-	0.102
232	149	4Mo-8V-6Cr-2.5Al	3.80	6.07	2.60	8.00	-	-	-	-	0.175
253	170	10Mo-8V-2.5Al	10.30	-	2.40	8.20	-	-	-	-	0.133
243	171	11Mo-1Al-0.5Si	10.60	-	0.90	-	-	-	0.50	-	0.109
227	169	7Mo-4Cr-2.5Al	6.70	4.18	2.70	-	-	-	-	-	0.109
216	172	8Mo-8V-2Fe-3Al	7.60	-	2.90	-	-	-	-	1.76	0.120
334	177	10Mo-6Cr-2.5Al	10.00	6.12	2.00	-	-	-	-	-	0.126
337	174	4Mo-6V-4Cr-2.5Al	3.80	4.09	3.73	6.18	-	-	-	-	0.126
338	175	4Mo-4Cr-4Zr-6Al-2Sn	4.00	4.08	6.40	-	4.12	2.31	-	-	0.103
339	176	2Mo-4V-4Cr-4Zr-6Al-2Sn	2.00	4.01	5.90	4.07	3.80	2.34	-	-	0.122
235	178	6Al-2Sn-4Zr-6Mo	6.20	-	6.20	-	4.12	2.42	-	-	0.106

[a] Determined by wet chemistry unless stated otherwise.
[b] Determined by atomic absorption and wet chemistry.
[c] Determined by vacuum fusion.

TABLE XXIV

EXPERIMENTALLY DETERMINED DENSITIES OF PHASE II ALLOYS

Alloy No.	Composition	Density ($lb.ins.^{-3}$) Measured[1]	Calculated[2]
232	4Mo-8V-6Cr-2.5Al	0.172	0.171
266	11Mo-4Al	0.170	0.169
261	9Mo-1.5Al-3Sn	0.174	0.172
227	7Mo-4Cr-2.5Al	0.171	0.169
253	10Mo-8V-2.5Al	0.175	0.173
216	8Mo-8V-2Fe-3Al	0.174	0.172

[1] Using the hydrostatic weighing technique and following ASTM procedure B311-58.

[2] Obtained using the rule of mixtures calculation.

TABLE XXV

ALLOYS FOR DETAILED FINE STRUCTURE ANALYSIS AT NORTH AMERICAN ROCKWELL SCIENCE CENTER

"Good" Alloys	Composition	Solution Treatment	Aging Temp. (F)	Aging Times [a]
227	7Mo-4Cr-2.5Al	1475F - 2 hr.	900	As Q, 1m, 5m, 8h, 48h
232	4Mo-8V-6Cr-2.5Al	1350F - 4 hr.	850	As Q, 10m, 30m, 3h, 24h
240	6Mo-6V	1325F - 4 hr.	800	As Q, 18s, 45s, 6m, 8h
243	11Mo-1Al-0.5Si	1475F - 2 hr.	950	As Q, 20s, 36s, 6m, 8h
253	10Mo-8V-2.5Al	1450F - 2 hr.	850	As Q, 20m, 1h, 48h, 96h
261	9Mo-1.5Al-3Sn	1475F - 2 hr.	850	As Q, 1m, 5m, 1½h, 8h
266	11Mo-4Al	1575F - 1 hr.	1000	As Q, 1m, 2m, 8h, 48h
"Bad" Alloys				
226	12V-2.5Al	1375F - 4 hr.	900	As Q, 12s, 30s, 12m, 8h
229	6Mo-3V-4Zr-7.5Sn	1450F - 2 hr.	950	As Q, 12s, 30s, 30m, 8h
242	5Mo-2Cr-2.5Al	1525F - 2 hr.	950	As Q, 12s, 30s, 30m, 8h

[a] Samples aged to $\frac{MH}{4}$, $\frac{MH}{2}$, MH and overage, where MH is maximum hardness.

TABLE XXVI

SUMMARY OF FINE STRUCTURE ANALYSIS

Alloy No.	Composition (bal. Ti)	Solution Treatment Temp. (F)	Solution Treatment Time (hr)	Temp. (F)	Phases Detected* β	α_p	α"	α"*	ω	α
227	7Mo-4Cr-2.5Al	1475	2	900	✓	✓	-	✓	-	✓
		1425	4	900	✓	✓	-	-	-	✓
226	12V-2.5Al	1375	4	900	✓	✓	✓	-	-	✓
240	6Mo-6V	1325	4	800	✓	✓	-	-	✓	✓
243	11Mo-1Al-0.5Si	1475	2	950	✓	✓	-	-	✓	✓
		1475	2	1000	✓	✓	-	-	✓	✓
		1425	4	950	✓	✓	-	-	-	✓
266	11Mo-4Al	1575	1	1000	✓	✓	-	-	-	✓
232	4Mo-8V-6Cr-2.5Al	1350	4	850	✓	✓	-	-	-	✓
		1300	4	850	✓	✓	-	-	-	✓
229	6Mo-3V-4Zr-7.5Sn	1450	2	950	✓	✓	-	✓	-	✓
261	9Mo-1.5Al-3Sn	1475	2	850	✓	✓	-	-	✓	✓
242	5Mo-2Cr-2.5Al	1525	2	950	✓	✓	-	✓	-	✓
253	10Mo-8V-2.5Al	1450	2	850	✓	✓	-	-	-	✓

*β - beta
α_p - primary alpha
α" - orthorhombic martensite
α"* - orthorhombic marteniste which reverts either during the early stages of aging or during heating to the aging temperature.
ω - omega
α - alpha

TABLE XXVII

PREDICTED DUCTILITY AND TOUGHNESS OF PHASE II ALLOYS AT CONTRACT YIELD STRENGTH GOAL

Alloy No.	Composition (bal. Ti.)	Contract[a] YS Goal (ksi)	Corresponding RA(%)	Corresponding K_Q (ksi√in.)
Contract Goals		170[b]	18	60
334	10Mo-6Cr-2.5Al	171	16	64
227	7Mo-4Cr-2.5Al	169	14	56
232	4Mo-8V-6Cr-2.5Al	171	17	~52
253	10Mo-8V-2.5Al	171	12	~59
337	4Mo-6V-4Cr-2.5Al	168	19	45
261	9Mo-1.5Al-3Sn	172	31	c
338	4Mo-4Cr-4Zr-6Al-2Sn	163	15	d
339	2Mo-4V-4Cr-4Zr-6Al-2Sn	162	c	d
266	11Mo-4Al	169	c	d
243	11Mo-1Al-0.5Si	172	c	c

[a] At a YS to density ratio of 1.0 x 10^6 inches.

[b] For an alloy of density 0.170 lbs/in.^{3}

[c] Value not defined precisely but obviously significantly below goal.

[d] Value not defined precisely, not considered to approach goal.

TABLE XXVIII

SUMMARY OF CORRELATION OF PROPERTIES TO MICROSTRUCTURE OF PHASE II SIMULATED COOLED AND AGED MATERIAL[a]

Alloy No.	Composition (bal. Ti)	Direction[b]	Yield Strength (ksi)	Redn. of Area (%)	K_Q (ksi$\sqrt{\text{in.}}$)[c]	Microstructure[d] $S\alpha$	$C\alpha$	$F\alpha$
261	9Mo-1.5Al-3Sn	T	167	46	11			
		L	160	37	~11	small amt.	globular	very fine
227	7Mo-4Cr-2.5Al	T	177	7	40			
		L	166	6	~40	present	lenticular	very fine
216	8Mo-8V-2Fe-3Al	T	194	20	36			
		L	194	13	~36	present	lenticular	med. fine
334	10Mo-6Cr-2.5Al	T	192	4	42			
		L	184	7	70	present	lenticular	med. fine
337	4Mo-6V-4Cr-2.5Al	T	199	5	29			
		L	198	9	30	present	lenticular	med. fine
235	6Al-2Sn-4Zr-6Mo	T	164	25	36			
		L	161	25	40	present	large amt. lenticular	small amt. med. fine

a For more details see Table VI.

b L = longitudinal, T = transverse.

c Approximate values have been estimated from data in Table VI.

d $S\alpha$ - Stringer alpha formed due to hot working.
$C\alpha$ - Coarse alpha formed at the solution treatment temperature.
$F\alpha$ - Fine alpha formed at the aging temperature by decomposition of the beta matrix.

TABLE XXIX

RELATIVE RANKING OF DUCTILITY AND FRACTURE TOUGHNESS ALLOY CHARACTERISTIC TREND LINES

Alloy No.	Composition (bal. Ti)	Relative[a] Ductility Ranking	Relative Fracture[b] Toughness Ranking
334	10Mo-6Cr-2.5Al	5	1
227	7Mo-4Cr-2.5Al	4	3
232	4Mo-8V-6Cr-2.5Al	3	4?
253	10Mo-8V-2.5Al	7	2?
337	4Mo-6V-4Cr-2.5Al	2	6
261	9Mo-1.5Al-3Sn	1	10?
338	4Mo-4Cr-4Zr-6Al-2Sn	6	7?
339	2Mo-4V-4Cr-4Zr-6Al-2Sn	8?	8?
266	11Mo-4Al	9	5?
243	11Mo-1Al-0.5Si	10	9?

[a] From Figures 44 through 53.

[b] From Figures 34 through 43.

? Best guess, characteristic trend line not defined precisely.

TABLE XXX

CHEMICAL ANALYSIS OF PHASE III ALLOY ADDITIONS

Addition	Oxygen	Nitrogen	Iron
Ti-Sponge, RSPI-31923	0.060*	0.010*	Nil
Mo granules, Mo #5	0.219	--	0.20
Electrolytic Cr, Cr-25	0.029	--	0.9
Al-Mo master (70:30) MY13	0.108	--	0.74
Al-V master (85:15), GY-141	0.210	--	0.40

* Analysis made on 50 gram button melt. Analysis for other alloy additions made on 50 gm buttons consisting of 10% alloy addition to Ti-sponge.

TABLE XXXI

CALCULATION OF ANTICIPATED Fe AND O_2 CONTENTS* OF DEEP HARDENABLE PHASE III 500 lb. INGOTS

Alloy No.	Composition (bal. Ti)	Fe (%)	O_2 (%)
334	10Mo-6Cr-2.5Al	0.13	0.08
227	7Mo-4Cr-2.5Al	0.10	0.10
253	10Mo-8V-2.5Al	0.08	0.11

* Based on analyses reported in Table XXX.

TABLE XXXII

CHEMICAL ANALYSIS OF PHASE III ALLOYS AT INGOT STAGE

Alloy	Location	Mo	Cr	Al	O_2
334	Goal	10	6	2.5	~0.100
	Top	9.44	6.03	2.6	0.103
	Bottom	9.44	ND*	3.5	0.106
	Collar	7.58	10.02	3.1	ND*
227	Goal	7	4	2.5	~0.100
	Top	6.85	ND*	2.6	0.123
	Bottom	6.01	ND*	ND*	ND*
	Collar	6.58	5.53	2.6	ND*
253	Goal	10	8	2.5	~0.100
	Top	10.73	7.9	2.5	ND*
	Bottom	9.02	8.4	2.5	ND*
	Collar	9.45	7.9	4.3	ND*

* Not determined.

TABLE XXXIII

CHEMICAL ANALYSIS OF PHASE III ALLOYS, BUTT END 10.5" RCS STAGE

Alloy	Mo	Cr	V	Al	O_2	H_2	N	C	Fe
334									
Nominal Composition	10.0	6.0	-	2.5	-	-	-	-	-
Actual Edge	9.88	6.06	-	2.4	.132	.0031	.008	.020	.06
Actual Center	9.88	6.30	-		.135	.0027			
227									
Nominal Composition	7.0	4.0	-	2.5	-	-	-	-	-
Actual Edge	6.73	4.10	-	2.4	.135	.0011	.012	.024	.08
Actual Center	6.73	4.07	-	2.4	.132	.0018	.007	.017	.10
253									
Nominal Composition	10.0	-	8.0	2.5	-	-	-	-	-
Actual Edge	10.02	-	8.0	2.6	.166	.0010	.014	.019	.09
Actual Center	9.88	-	8.0	2.6	.168	.0004	.012	.012	.09

TABLE XXXIV

ALLOY DENSITY*

Alloy	Composition (bal Ti)	Density (lb/cubic inch) Location Edge	Center
334	10Mo-6Cr-2.5Al	0.171	0.171
227	7Mo-4Cr-2.5Al	0.169	0.169
253	10Mo-8V-2.5Al	0.171	0.171

* One quarter (¼) inch cube samples in all beta condition tested using ASTM procedure B311-58.

TABLE XXXV

BETA RECRYSTALLIZATION STUDY

Alloy	Composition (bal Ti)	Beta Transus (F)	Anneal* Temp. (F)	Anneal* Time (hr)	Percent Recrystallized
334	10Mo-6Cr-2.5Al	1425	1600	4	25
227	7Mo-4Cr-2.5Al	1525	1550	4	35-40
253	10Mo-8V-2.5Al	1425	1600	4	25-30

* Anneal for optimum recrystallization. Reduced time-temperature resulted in less recrystallization; increased time-temperature caused only an overall increase in grain size.

TABLE XXXVI

FORGING SCHEDULE FOR TMT OPTIMIZATION TO 6 INCH DIAMETER

Alloy	Location[a]	Sample[b]	Forging Route[c]	Forge Temp.(F)*	Re-heat Temp.(F)*	Processing Code
334	C	BR	HTMT	1550	1475	A
	C	BR	LTMT	1450	1400	B
	C	No BR	LTMT	1450	1400	C
	E	BR	HTMT	1500	1425	A
	E	BR	LTMT	1400	1350	B
	E	No BR	LTMT	1400	1350	C
253	C	BR	HTMT	1550	1475	A
	C	BR	LTMT	1450	1400	B
	C	No BR	LTMT	1450	1400	C
	E	BR	HTMT	1550	1475	A
	E	BR	LTMT	1450	1400	B
	E	No BR	LTMT	1450	1400	C
227	C	BR	HTMT	1650	1575	A
	C	BR	LTMT	1550	1500	B
	C	No BR	LTMT	1550	1500	C
	E	BR	HTMT	1650	1575	A
	E	BR	LTMT	1550	1500	B
	E	No BR	LTMT	1550	1500	C

[a] C - center; E - edge.

[b] BR - beta recrystallized; No BR - no beta recrystallization.

#334: 1600F - 4 hr AC.
#227: 1550F - 4 hr AC.
#253: 1600F - 4 hr AC.

[c] HTMT - high temperature thermomechanical process.
LTMT - low temperature thermomechanical process.

* Related to beta transus:
#334: 1425F
#227: 1525F
#253: 1425F

TABLE XXXVII

SOLUTION AND AGING TREATMENTS FOR TMT OPTIMIZATION TO 6 INCH DIAMETER

Alloy	Location[a]	Processing[b] Code	Heat Treatment: Solution Temp (F)	Solution Time (hr)	Age Temp (F)	Age Time (hr)	Processing and Heat Treatment Code[c]
334	C & E	A	1350	4	950	96	AIa
			1350	4	900	96	AIb
		B	1350	4	900	96	BIb
			1300	4	900	96	BIIb
		C	1350	4	950	96	CIa
			1300	4	950	96	CIIa
253	C & E	A	1325	4	950	96	AIa
			1325	4	900	96	AIb
		B	1325	4	900	96	BIb
			1275	4	900	96	BIIb
		C	1325	4	950	96	CIa
			1275	4	950	96	CIIa
227	C & E	A	1475	2	975	8	AIa
			1475	4	925	8	AIb
		B	1475	2	925	8	BIb
			1425	4	925	8	BIIb
		C	1475	2	975	8	CIa
			1425	4	975	8	CIIa

[a] Center and edge samples to receive same treatment.

[b] See final column of Table XXXVI.

[c] First letter indicates the processing route, numeral the solution annealing treatment and final letter the aging treatment.

TABLE XXXVIII

MECHANICAL PROPERTIES OF ALLOY 334 (10Mo-6Cr-2.5Al) AFTER SIMULATED PROCESSING FROM 10.5" RCS to 6" STAGE

		Heat Treatment			Mechanical Properties						
Location[a]	Proc. Sch.[b]	Solution[c]	Age[d]	Code[e]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	K_Q[f] (ksi$\sqrt{in.}$)
Approx. Goal*					186.0	178.0	10.0	15.0			55.0
C	A	I	a	1C	178.6	173.7	11.0	30.6	16.5	C	106.5
					184.9	179.8	8.0	33.2	16.7	C	101.1
		I	b	2C	192.4	186.7	8.0	19.6	15.9	B	80.4
					189.9	186.1	5.0	26.6	16.0	C	91.6
	B	I	b	3C	192.4	186.1	6.0	16.8	16.2	C	136.5
					192.9	187.0	8.0	18.2	16.7	C	73.9
		II	b	4C	179.4	176.8	6.0	20.2	16.2	C	123.2
					181.9	175.9	10.0	29.2	16.2	C	114.2
	C	I	a	5C	185.4	180.4	7.0	21.6	16.1	C	118.5
					184.6	180.1	12.0	23.8	16.9	A	104.4
		II	a	6C	180.9	174.9	10.0	15.2	17.1	A	112.0
					176.9	171.9	8.0	27.2	16.8	C	85.9
E	A	I	a	1E	181.4	175.9	9.0	28.6	16.9	C	110.4
					183.4	177.1	9.0	21.6	16.6	C	128.1
		I	b	2E	205.9	198.4	7.0	15.2	17.3	A	77.9
					200.9	193.9	8.0	17.4	17.1	C	80.2
	B	I	b	3E	190.9	184.3	7.0	15.2	16.7	B	77.9
					201.4	194.8	12.0	12.4	17.0	C	74.8
		II	b	4E	192.2	186.4	7.0	12.4	17.3	B	85.1
					192.2	187.0	-	-	17.2	OGM	92.4
	C	I	a	5E	179.2	174.3	8.0	27.8	16.7	B	83.2
					178.4	175.9	5.0	13.8	17.3	C	-
		II	a	6E	177.9	173.7	6.0	18.2	16.8	C	119.3
					183.3	178.2	7.0	7.8	17.0	C	131.3

[a] C - center, E - edge of 10.5" RCS billet.

[b] A - Beta recrystallization (BR) + high temperature thermomechanical process (HTMT);
B - BR + low temperature TMT (LTMT);
C - No BR + LTMT.

BR: 4 hour - 1600F AC
HTMT: forge from 1550F, reheats 1475F.
LTMT: forge from 1450F, reheats 1400F.

[c] I - 1350F - 4 hours
II - 1300F - 4 hours

[d] a - 950F - 96 hours
b - 900F - 96 hours

[e] To enable direct comparison of various conditions.

[f] Slow bend of precracked Charpy samples. Calculated using $K_Q = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* To reach contract goals at center of six inch section.

TABLE XXXIX

MECHANICAL PROPERTIES OF ALLOY 227 (7Mo-4Cr-2.5Al)
AFTER SIMULATED PROCESSING FROM 10.5" RCS TO 6" STAGE

Location[a]	Proc. Sch.[b]	Heat Treatment Solution[c]	Heat Treatment Age[d]	Code[e]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$)	Break	K_Q[f] (ksi√in.)
Approx. Goal*					190.0	184.0	9.0	14.0			50.0
C	A	I	a	1C	197.2	190.1	4.0	14.8	16.6	C	65.3
					198.6	192.2	6.0	14.2	15.9	C	84.5
		I	b	2C	210.3	200.0	3.0	15.0	16.2	A	67.7
					201.5	195.0	3.0	13.2	16.1	C	60.6
	B	I	b	3C	210.4	201.4	2.0	1.6	16.9	C	57.1
					206.4	198.7	2.0	3.2	16.3	OGM	49.6
		II	b	4C	197.0	186.0	5.0	8.0	16.8	B	86.6
					198.4	188.8	8.0	20.2	17.6	B	68.5
	C	I	a	5C	204.4	195.4	8.0	14.6	16.8	A	149.9
					202.0	192.0	8.0	19.8	17.2	A	80.0
		II	a	6C	195.0	186.3	3.0	8.8	17.9	C	100.5
					191.9	183.3	9.0	18.9	16.9	C	108.8
E	A	I	a	1E	206.4	196.9	4.0	10.0	16.9	B	82.1
					188.3	180.1	7.0	24.3	15.5	B	106.3
		I	b	2E	211.5	204.3	3.0	13.2	17.4	C	63.4
					210.4	202.0	3.0	10.0	15.9	C	74.5
	B	I	b	3E	210.4	203.8	2.0	4.8	16.7	OGM	114.8
					205.5	196.2	6.0	13.2	17.9	A	64.9
		II	b	4E	203.0	190.5	6.0	14.0	17.4	B	98.1
					206.4	195.4	6.0	4.0	17.4	B	103.4
	C	I	a	5E	206.4	198.4	-	-	17.0	OGM	123.8
					204.0	198.0	5.0	10.2	17.2	C	74.5
		II	a	6E	187.4	177.4	10.0	28.6	17.4	A	110.5
					185.9	178.9	6.0	22.4	17.0	C	113.0

[a] C - center, E - edge of 10.5" RCS billet.

[b] A - beta recrystallization (BR) + high temperature thermomechanical process (HTMT);
B - BR + low temperature TMT (LTMT);
C - no BR + LTMT.
BR: 4 hour - 1550F AC
HTMT: forge from 1650F, reheats 1575F.
LTMT: forge from 1550F, reheats 1500F.

[c] I - 1475F - 2 hours
II - 1425F - 4 hours

[d] a - 975F - 8 hours
b - 925F - 8 hours

[e] To enable direct comparison of various conditions.

[f] Slow bend of precracked Charpy samples. Calculated using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* To reach contract goals at center of six inch section.

TABLE XL

MECHANICAL PROPERTIES OF ALLOY 253 (10Mo-8V-2.5Al) AFTER SIMULATED PROCESSING FROM 10.5" RCS TO 6" STAGE

Location[a]	Proc.[b] Sch.	Heat Treatment Solution[c]	Heat Treatment Age[d]	Code[e]	Mechanical Properties UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	K_Q[f] (ksi/in.)
Approx. Goal*					180.0	174.0	10.0	16.0			55.0
C	A	I	a	1C	167.3	165.3	9.0	18.0	15.5	C	93.5
					164.8	162.3	-	-	15.9	OGM	104.4
		I	b	2C	189.9	184.0	4.0	7.8	16.4	C	76.2
					188.7	184.3	4.0	13.0	16.2	C	77.7
	B	I	b	3C	189.9	183.1	2.0	5.6	16.8	C	92.7
					191.1	185.3	8.0	20.0	17.2	C	88.8
		II	b	4C	176.6	169.9	7.0	17.9	16.6	B	106.6
					180.0	173.7	6.0	16.2	16.4	A	117.4
	C	I	a	5C	167.8	163.8	11.0	43.1	15.9	B	93.7
					165.3	162.0	10.0	28.3	15.9	B	83.4
		II	a	6C	163.3	157.2	9.0	36.5	16.9	C	97.6
					168.8	166.8	10.0	30.7	16.3	C	117.0
E	A	I	a	1E	177.4	171.9	4.0	5.6	17.2	B	89.0
					168.3	166.8	5.0	18.8	16.2	C	92.4
		I	b	2E	176.4	171.9	6.0	21.6	15.7	A	75.7
					185.4	180.4	6.0	7.0	16.8	A	94.3
	B	I	b	3E	181.7	177.7	6.0	26.5	16.8	B	84.9
					195.4	183.7	2.0	4.8	19.1	C	118.1
		II	b	4E	183.9	178.6	8.0	16.8	18.6	C	93.4
					180.4	174.4	11.0	33.9	16.7	B	99.7
	C	I	a	5E	177.9	173.2	8.0	15.0	17.3	B	80.6
					176.2	171.7	6.0	18.1	18.4	C	70.2
		II	a	6E	153.8	151.2	8.0	32.5	16.0	C	110.1
					166.0	-	-	-		OGM	96.0

[a] C - center, E - edge of 10.5" RCS billet.

[b] A - Beta recrystallization (BR) + high temperature thermomechanical process (HTMT);
B - BR + low temperature TMT (LTMT);
C - No BR + LTMT.

BR: 4 hour - 1600F AC
HTMT: forge from 1550F, reheats 1475F
LTMT: forge from 1450F, reheats 1400F

[c] I - 1325F - 4 hours
II - 1275F - 4 hours

[d] a - 950F - 96 hours
b - 900F - 96 hours

[e] To enable direct comparison of various conditions.

[f] Slow bend of precracked Charpy samples. Calculated using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1 - \nu^2)}$

* To reach contract goals at center of six inch section.

TABLE XLI

HARDNESS OF ALLOY 334(10Mo-6Cr-2.5Al) AFTER DUPLEX HEAT TREATMENT CYCLES

Aging Treatments[a] I Temp (F)	I Time (hrs)	II Temp (F)	II Time (hrs)	III Temp (F)	III Time (hrs)	Hardness (VPN)	UTS (ksi)
						400† Goal	188
--	--	--	--	925	8	311	
--	--	--	--	925	24	332	
--	--	--	--	925	96	350@	
650	8	--	--	925	8	335	
650	8	--	--	925	24	341	
650	8	--	--	925	96	344	
650	24	--	--	925	8	350	
650	24	--	--	925	24	359	
650	24	--	--	925	96	353	
--	--	750	8	925	8	366	
--	--	750	8	925	24	372	
650	8	750	8	925	8	363	
650	8	750	8	925	24	*	

[a] After solution treatment 1300F - 4 hours WQ.

* Sample lost.

† Calculated from UTS value (Second Interim, page 43).

@ UTS after this treatment was 179 ksi (Fifth Interim, page 32).

TABLE XLII

FURTHER MECHANICAL PROPERTIES OF ALLOY 334 (10Mo-6Cr-2.5Al) AFTER SIMULATED PROCESSING FROM 10.5" RCS TO 6" STAGE

		Heat Treatment							Mechanical Properties						
		Solution Treatment		Pre-Age		Age									
Location[a]	Proc. Sch.[b]	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Code[c]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	K_Q[d] (ksi$\sqrt{in.}$)
Approx. Goal*									186.0	178.0	10.0	15.0			55.0
C	A	1350	4	750	8	925	8	7C	195.4	190.9	3.0	16.0	16.6	C	69.2
									195.6	188.6	7.0	17.8	16.6	C	68.0
E								7E	202.5	197.7	6.0	8.0	16.6	C	61.8
									197.9	193.6	-	-	15.9	OGM	66.1
C	B	1350	4	750	8	1025	8	8C	173.0	169.6	16.0	36.8	13.6	B	81.4
									177.3	174.8	8.0	19.6	14.4	B	74.2
E								8E	167.2	164.5	14.0	29.3	14.5	A	91.1
									170.0	166.0	8.0	17.1	14.5	C	129.8
C	C	1250	4	750	8	925	8	9C	169.0	164.1	10.0	31.6	14.4	C	96.6
									170.3	167.7	10.0	26.7	14.0	C	115.6
E								9E	178.1	172.7	12.0	35.0	14.9	B	114.2
									172.6	168.2	10.0	21.2	15.6	C	109.3

a C - center, E - edge of 10.5" RCS billet.

b A - Beta recrystallization (BR) + high tenperature thermomechanical process (HTMT);
B - BR + low temperature TMT (LTMT);
C - No BR + LTMT.

BR: 4 hour - 1600F AC
HTMT: forge from 1550F, reheats 1475F.
LTMT: forge from 1450F, reheats 1400F.

c To enable direct comparison of various conditions.

d Slow bend of precracked Charpy samples. Calculated using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* To reach contract goals at center of six inch section.

TABLE XLIII

FURTHER MECHANICAL PROPERTIES OF ALLOY 253 (10Mo-8V-2.5Al) AFTER SIMULATED PROCESSING FROM 10.5" RCS TO 6" STAGE

		Heat Treatment							Mechanical Properties						
		Solution Treatment		Pre-Age		Age									
Location[a]	Proc. Sche.[b]	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Code[c]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E (x10^6 psi)	Break	K_Q[d] (ksi/in.)
Approx. Goal*									180.0	174.0	10.0	16.0			55.0
C	C	1275	4	750	8	900	8	7C	176.9	169.8	10.0	21.0	13.9	B	75.7
									175.9	168.9	9.0	22.4	13.8	A	73.3
E								7E	179.4	174.3	5.0	17.4	16.6	C	87.1
									182.9	175.9	5.0	13.8	16.9	C	78.2

[a] C - center, E - edge of 10.5" RCS billet.

[b] A - Beta recrystallization (BR) + high temperature thermomechanical process (HTMT);
B - BR + low temperature TMT (LTMT);
C - No BR + LTMT.

BR: 4 hour - 1600F AC.
HTMT: forge from 1550F, reheats 1475F.
LTMT: forge from 1450F, reheats 1400F.

[c] To enable direct comparison of various conditions.

[d] Slow bend of precracked Charpy samples. Calculated using $K^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* To reach contract goals at center of six inch section.

TABLE XLIV

FURTHER MECHANICAL PROPERTIES OF ALLOY 227 (7Mo-4Cr-2.5Al) AFTER SIMULATED PROCESSING FROM 10.5" RCS TO 6" STAGE

		Heat Treatment							Mechanical Properties						
		Solution Treatment		Pre-Age		Age									
Location[a]	Proc. Sch.[b]	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Code[c]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	K_Q[d] (ksi√in.)
Approx. Goal*									190.0	184.0	9.0	14.0			50.0
C	C	1475	2	--	--	1000	8	7C	200.4	186.4	6.0	11.4	15.7	C	82.0
									195.4	189.4	5.0	15.6	14.6	C	75.5
E								7E	185.4	177.4	8.0	27.7	14.8	C	103.3
									192.9	183.4	4.0	9.2	14.9	C	66.3
C	C	1475	2	-	-	1025	8	8C	196.4	190.6	8.0	15.2	15.4	C	74.4
									192.9	186.4	8.0	22.4	15.7	C	80.0
E								8E	191.2	187.0	-	-	16.7	OGM	99.7
									184.9	178.[illegible]	[illegible]1.0	12.8	16.6	A	108.5
C	C	1400	4	--	--	925	8	9C	194.4	186.[illegible]	[illegible].0	14.2	15.0	C	77.3
									194.4	184.[illegible]	[illegible].0	22.4	16.3	C	67.9
E								9E	196.4	187.9	-	-	15.9	OGM	98.1
									189.4	180.4	6.0	26.6	15.6	C	117.5
C	C	1375	4	--	--	925	8	10C	194.4	186.4	-	-	16.5	OGM	83.9
									180.8	168.0	5.0	16.0	15.8	C	84.1
E								10E	187.9	178.9	8.0	24.6	16.1	C	130.1
									185.4	175.9	8.0	29.0	15.6	C	56.8
C	A	1475	2	925	2	1025	8	11C	188.4	183.9	8.0	14.5	14.8	A	86.2
									175.9	171.3	12.0	55.1	13.4	A	75.8
E								11E	194.7	187.1	5.0	10.5	16.2	B	74.7
									190.2	183.2	6.0	9.1	16.7	A	81.4
C	B	1475	2	--	--	1050	8	12C	181.4	175.6	10.0	36.5	15.9	A	145.5
									184.6	176.6	10.0	23.5	17.7	A	132.7
E								12E	188.1	181.1	10.0	26.4	16.8	A	120.3
									187.4	180.3	8.0	22.4	15.6	C	106.3

[a] C - center, E - edge of 10.5" RCS billet.

[b] A - beta recrystallization (BR) + high temperature thermomechanical process (HTMT);
B - BR + low temperature TMT (LTMT);
C - no BR + LTMT.

BR: 4 hour - 1550F AC
HTMT: forge from 1650F, reheats 1575F
LTMT: forge from 1550F, reheats 1500F

[c] To enable direct comparison of various conditions.

[d] Slow bend of precracked Charpy samples. Calculated using $K^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* To reach contract goals at center of six inch section.

TABLE XLV

SUMMARY OF TMT OPTIMIZATION STUDY,*
10.3 INCH RCS TO 6 INCH DIAMETER ROUND

	Optimum TMT			
Alloy	RA Code	K_Q Code	Overall Code[a]	Overall Treatment
334	AIb	AIIb	AIIb	BR + Hi Proc. + Lo ST + Lo Age
227	CIb	CI-	CIb	No BR + Lo Proc. + Hi ST + Lo Age
253	CIIb	BIb	BIIb	BR + Lo Proc. + Lo ST + Lo Age

* See Tables XXXVI - XL and XLII - XLIV and Figures 77 - 82, where details of treatments and coding are given.

[a] Note that only in the case of alloy 253 is the overall optimum treatment actually shown in the figure, BIIb (#4 Figures 81 and 82).

TABLE XLVI

OPTIMUM TMT TO CONVERT BLOOMS FROM 10.5 INCH RCS TO 6 INCH ROUND BILLETS

Alloy 334(10Mo-6Cr-2.5Al)

1. Beta recrystallize 4 hr. at 1600F.
2. Upset forge from 1550F and draw out to 6¼" bar, reheats at 1475F.
3. With a subsequent 1300F - 4 hr. solution treatment and 900F - 96 hour age anticipated longitudinal edge properties:
   180 ksi (YS) 25% (RA) 110 ksi√in. (K_QLT or LS)

Alloy 227(7Mo-4Cr-2.5Al)

1. No beta recrystallization.
2. Upset forge from 1550F and draw out to 6¼" bar, reheats at 1500F.
3. With a subsequent 1475F - 2 hr. solution treatment and 1025F - 8 hr. age, anticipated longitudinal edge properties:
   185 ksi (YS) 18% (RA) 90 ksi√in. (K_Q LT or LS)

Alloy 253(10Mo-8V-2.5Al)

1. Beta recrystallization 4 hr. at 1600F.
2. Upset forge from 1450F and draw out to 6¼" bar, reheats at 1400F.
3. With a subsequent 1275F - 4 hr. solution treatment and 900F - 96 hr. age, anticipated longitudinal edge properties:
   174 ksi (YS) 21% (RA) 103 ksi√in. (K_Q LT or LS)

TABLE XLVII
MECHANICAL PROPERTIES OF ALLOY 334 (10Mo-6Cr-2.5Al) AT 6" STAGE, SAMPLES FROM BUTT END SLICES

Solution Treatment Temp. (F)	Solution Treatment Time (hr)	Cool Route[a]	Aging Temp. (F)	Aging Time (hr)	Loc.[b]	Dirn.[c]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	K_Q[d] LR	K_Q[d] LT	K_Q[d] SR	K_Q[d] SL
1300	4	SC	900	96	C	L	183.9	176.2	10.0	30.6	15.5	C	106.4	-	-	-
							173.9	165.3	14.0	29.9	14.9	C	90.6	-	-	-
						T	177.9	171.3	4.0	13.0	15.7	C	-	-	60.7	
							187.4	177.4	3.0	6.4	16.7	A	-	-	53.4	
		WQ			C	L	183.9	177.4	12.0	27.7	15.3	A	97.7	-	-	-
					E	L	191.9	178.6	6.0	11.6	15.6	B	87.9	98.7	-	-
							193.9	186.4	8.0	17.8	16.1	C	80.3	*126.7	-	-
						T	193.4	185.8	1.0	5.4	16.5	B	-	-	49.1	51.7
							194.4	184.9	2.0	2.0	16.0	C	-	-	65.3	*48.6

[a] SC - Simulated cool: 1100F - 118 secs.
900F - 58 secs.
700F - 62 secs.
then air cool

WQ - Water quench

[b] Location: C - Center; E - Edge.

[c] Direction: L - Longitudinal; T - Transverse.

[d] Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* Used for structural analysis.

TABLE XLVIII

MECHANICAL PROPERTIES OF ALLOY 227 (7Mo-4Cr-2.5Al)
AT 6" STAGE, SAMPLES FROM BUTT END SLICES

Solution Treatment Temp. (F)	Solution Treatment Time (hr)	Cool Route[a]	Aging Temp. (F)	Aging Time (hr)	Loc.[b]	Dirn.[c]	Mechanical Properties UTS (ksi)	YS (ksi)	El (%)	RA (%)	E (x10^6 psi)	Break	K_Q[d] LR	LT	SR	SL
1475	2	SC	1025	8	C	L	183.9	169.2	12.0	30.6	16.0	C	86.2	-	-	-
							183.9	168.2	10.0	27.3	15.8	C	96.2	-	-	-
						T	188.4	175.0	2.0	4.8	17.6	C	-	-	53.5	
							188.4	161.4	4.0	11.6	15.2	C	-	-	66.3	
		WQ			E	L	177.4	171.4	10.0	30.1	14.7	C	56.6*	69.7	-	-
							183.4	175.6	6.0	16.8	15.0	C	61.9	74.6	-	-
						T	177.9	172.2	4.0	15.2	14.5	C	-	-	54.9*	54.4
							177.4	170.1	3.0	9.4	14.8	C	-	-	47.0	
			900 plus 1050	96 8	C	L	185.9	175.6	9.0	28.5	15.2	B	85.3	-	-	-
					E	L	191.9	184.9	7.0	22.8	15.0	C	72.2*	69.1	-	-
							187.4	180.1	12.0	32.1	15.2	C	83.7	68.2	-	-
						T	185.9	179.2	7.0	6.0	15.4	C	-	-	37.5	34.3
							195.4	185.8	3.0	6.4	15.2	C	-	-	43.6*	

[a] SC - Simulated cool: 1275F - 117 secs.
1075F - 50 secs.
875F - 55 secs.
then air cool

WQ - Water quench

[b] Location: C - Center; E - Edge

[c] Direction: L - Longitudinal; T - Transverse

[d] Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* Used for structural analysis.

TABLE XLIX

MECHANICAL PROPERTIES OF ALLOY 253 (10Mo-8V-2.5Al) AT 6" STAGE, SAMPLES FROM BUTT END SLICES

Solution Treatment Temp. (F)	Solution Treatment Time (hr)	Cool Route[a]	Aging Temp. (F)	Aging Time (hr)	Loc.[b]	Dirn.[c]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	K_Q[d] LR	K_Q[d] LT	K_Q[d] SR	K_Q[d] SL
1275	4	SC	900	96	C	L	172.3	163.8	14.0	41.9	15.3	C	79.0	-	-	-
							180.8	173.4	12.0	32.5	15.6	C	88.4	-	-	-
						T	173.3	166.2	4.0	16.8	15.1	C	-	-	60.2	
							179.4	171.3	5.0	11.6	14.7	C	-	-	74.1	
		WQ			C	L	183.9	175.9	13.0	29.9	15.0	C	104.5	-	-	-
					E	L	177.4	172.2	7.0	31.3	14.7	C	81.7	84.6	-	-
							179.9	171.9	8.0	29.9	16.0	C	74.4*	131.3	-	-
						T	178.4	167.7	3.0	7.0	15.6	C	-	-	44.6	41.1
							171.3	165.3	3.0	19.6	15.3	C	-	-	50.9*	48.6

[a] SC - Simulated cool: 1075F - 120 secs.
875F - 58 secs.
675F - 64 secs.
then air cool

WQ - Water quench

[b] Location: C - Center; E - Edge

[c] Direction: L - Longitudinal; T - Transverse

[d] Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* Used for structural analysis.

TABLE L

MECHANICAL PROPERTIES OF ALLOY 334 (10Mo-6Cr-2.5Al)
AT 10.5" STAGE, SAMPLES FROM BUTT END

Heat Treatment					Mechanical Properties							
Solution Treatment[a]		Age			Tensile						K_Q[c] (ksi√in.)	
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Dirn.[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E (x 10^6 psi)	Break	RW	SL
1300	4	900	96	L	179.9	177.4	5.0	13.0	17.0	A	98.7	-
				T	190.9	183.4	3.0	9.4	17.6	C	-	59.9 *
					186.1	180.4	4.0	7.8	16.7	C	-	
-	-			L	209.3	201.8	3.0	5.4	16.8	C	57.8	-
				T	206.9	201.4	2.0	6.4	17.0	C	-	47.1
					209.4	204.4	2.0	7.0	15.9	C	-	47.3

[a] Followed by a WQ

[b] L - longitudinal
T - transverse

[c] Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* Used for structural analysis.

TABLE LI

MECHANICAL PROPERTIES OF ALLOY 227 (7Mo-4Cr-2.5Al) AT 10.5" STAGE, SAMPLES FROM BUTT END

Heat Treatment					Mechanical Properties							
Solution Treatment[a]		Age			Tensile						K_Q[c] (ksi√in.)	
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Dirn.[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E (x 10^6 psi)	Break	RW	SL
1475	2	1025	8	L	191.4	183.4	4.0	13.0	15.7	B	52.6	-
				T	186.4	178.9	3.0	11.6	15.3	A	-	56.9
					194.3	187.6	1.0	7.6	16.0	OGM	-	56.2*
											105.9	
-	-			L	151.1	144.6	10.0	31.1	16.0	C		-
				T	155.6	145.5	8.0	27.1	15.6	A	-	90.0
					155.8	146.4	5.0	10.8	16.2	A	-	98.5

[a] Followed by a WQ

[b] L - longitudinal
T - transverse

[c] Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* Used for structural analysis.

TABLE LII

RECRYSTALLIZATION KINETICS STUDY OF ALLOYS 334(10Mo-6Cr-2.5Al) AND 227(7Mo-4Cr-2.5Al) AT 6 INCH BILLET STAGE

Alloy	βT (°F)	Temperature[a] (°F)	Annealing Times[b] Mins.	Hours
334	1425	1525	5	0.5, 5
		1400	-	0.5, 5
227	1525	1575	5	0.5, 5
		1500	-	0.5, 5

[a] Followed by a water quench.

[b] At temperature.

TABLE LIII

MECHANICAL PROPERTIES OF ALLOY 334 (10Mo-6Cr-2.5Al)
AT 6" STAGE, SUPRA-TRANSUS RECRYSTALLIZED PRIOR TO HEAT TREATMENT,
SAMPLES FROM BUTT END

Recrystallization Anneal[a]		Heat Treatment: Solution Treatment[a]		Heat Treatment: Age			Mechanical Properties: Tensile						K_Q[c] (ksi√in.)	
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Dirn.[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E (x 10^6 psi)	Break	LR	SL
1525	1	-	-	900	96	L	212.9	205.3	2.0	7.0	16.4	A	49.4	-
						T	197.8	197.3	2.0	5.4	15.7	A	-	44.2
							222.9	222.4	2.0	5.6	16.9	OGM	-	40.2
		1300	4			L	172.3	166.9	4.0	14.3	16.1	C	57.9	-
						T	182.7	177.7	2.0	5.4	16.3	A	-	44.6
							182.6	178.1	2.0	6.6	16.1	C	-	45.5 *

[a] Followed by a WQ

[b] L - longitudinal
T - transverse

[c] Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* Used for structural analysis.

TABLE LIV

MECHANICAL PROPERTIES OF ALLOY 227 (7Mo-4Cr-2.5Al)
AT 6" STAGE, SUPRA-TRANSUS RECRYSTALLIZED PRIOR TO HEAT TREATMENT
SAMPLES FROM BUTT END

Recrystallization Anneal[a]		Heat Treatment: Solution Treatment[a]		Heat Treatment: Age			Mechanical Properties: Tensile						K_Q[c] (ksi√in.)	
Temp (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Dirn.[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E (x 10^6 psi)	Break	LR	SL
1575	0.5	-	-	1025	8	L	192.4	184.1	3.0	6.0	15.8	C	60.4	-
						T	190.2	185.6	2.0	4.5	15.1	A	-	54.6
							195.4	184.3	1.0	4.8	15.2	C	-	50.5
		1475	2			L	189.0	180.1	1.0	5.4	15.0	A	56.9	-
						T	199.0	190.4	1.0	6.2	15.9	A	-	39.3
							193.8	185.8	1.0	6.2	15.4	A	-	43.4*

[a] Followed by a WQ

[b] L - longitudinal
T - transverse

[c] Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1 \nu^2)}$

* Used for structural analysis.

TABLE LV

MECHANICAL PROPERTIES OF ALLOY 227 (7Mo-4Cr-2.5Al) GIVEN AN ISOTHERMAL TREATMENT PRIOR TO AGING. SAMPLES AT 6" STAGE BUTT END SLICE

Annealing Treatment				Age			Tensile Properties					
First[a]		Second[a]										
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Direction[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E (x 10^6 psi)	Break
1500	2	1425	0.25	925	8	T	198.4	190.0	1.0	5.6	15.0	C
							209.4	198.4	2.0	5.6	16.0	C
		1375	0.25			T	184.0	165.3	4.0	12.6	15.7	C
							189.4	182.8	-	-	15.1	OGM

[a] Directly transferred to Second Furnace (isothermally).

[b] T - transverse.

TABLE LVI

FURTHER MECHANICAL PROPERTIES OF ALLOY 227(7Mo-4Cr-2.5Al)
GIVEN AN ISOTHERMAL TREATMENT PRIOR TO AGING
SAMPLES AT 6" STAGE BUTT END SLICE

Annealing Treatment: First[a] Temp. (F)	First[a] Time (hr)	Second[b] Temp. (F)	Second[b] Time (hr)	Third[a] Temp. (F)	Third[a] Time (hr)	Fourth[b] Temp. (F)	Fourth[b] Time (hr)	Age Temp. (F)	Age Time (hr)	Direction[c]	Tensile Properties: UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break
1500	5	1425	0.25	-	-	-	-	1025	8	T	184.7	176.0	3.0	4.7	17.0	A
											184.0	177.7	2.0	6.2	17.3	C
1500	5	1425	1	-	-	-	-	1000	8	T	184.8	178.0	2.0	11.6	18.4	C
											185.5	180.8	2.0	9.1	17.6	C
1500	2	1425	1	1500	3	1425	0.25	1025	8	T	181.1	173.8	4.0	5.8	17.6	B
											186.6	184.9	4.0	8.6	16.9	C

[a] Directly transferred to next furnace (isothermally).

[b] Air cooled.

[c] T - transverse.

TABLE LVII

ADDITIONAL* MECHANICAL PROPERTIES OF ALLOY 227 (7Mo-4Cr-2.5Al) AT 6" STAGE DUPLEX ISOTHERMAL (HIGH-LOW) ANNEAL PRIOR TO AGE, SAMPLES FROM BUTT END

Annealing Treatment First[a] Temp. (F)	Annealing Treatment First[a] Time (hr)	Annealing Treatment Second[b] Temp. (F)	Annealing Treatment Second[b] Time (hr)	Age Temp. (F)	Age Time (hr)	Direction[c]	Tensile Properties UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break
1500	5	1325	2	950	8	T	158.6	144.8	4.0	9.7	15.9	C
							163.0	150.9	4.0	11.3	17.4	A
				1000	8	T	156.7	147.8	8.0	8.2	16.2	B
							150.1	143.7	10.0	26.4	16.0	B

* Isothermal treatments revised on basis of promising normal high-low annealing.

a Directly transferred to next furnace (isothermally).

b Air cooled.

c L - longitudinal, T - transverse.

TABLE LVIII

MECHANICAL PROPERTIES OF ALLOY 334 (10Mo-6Cr-2.5AL) AT 6" STAGE DUPLEX (LOW-HIGH) ANNEAL PRIOR TO AGE, SAMPLES FROM BUTT END

Annealing Treatment						Age			Mechanical Properties							
Low[a]		High							Tensile						K_Q[c] (ksi√in.)	
		First		Second												
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Dirn.[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E (x10⁶ psi)	Break	LR	SR
1250	8	1350	100	-	-	950	96	T	170.3	170.0	4.0	7.8	15.7	C	-	36.6
									180.8	175.6	2.0	7.0	15.8	C	-	127.3?
								L	174.5	172.1	12.0	33.9	15.3	B	118.2	-
1250	8	1375	24	1325	100	950	96	T	170.5	167.4	2.0	6.2	15.5	A	-	57.1 *
									175.9	173.4	2.0	6.6	17.0	C	-	63.5
								L	168.9	165.5	14.0	31.3	15.2	A	94.6	

* Used for structural analysis.

a Followed by a water quench.

b L - longitudinal, T - transverse.

c Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

? Questionable value.

TABLE LIX

MECHANICAL PROPERTIES OF ALLOY 227 (7Mo-4Cr-2.5Al) AT 6" STAGE DUPLEX (LOW-HIGH) ANNEAL PRIOR TO AGE, SAMPLES FROM BUTT END

Annealing Treatment									Mechanical Properties							
Low[a]		High First		High Second		Age			Tensile						K_Q[c] (ksi√in.)	
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Dirn.[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	LR	SR
1350	8	1450	100	-	-	1025	8	T	175.9	171.2	1.0	5.6	16.3	C	-	46.9
									180.8	180.6	-	-	15.6	OGM	-	51.4
1350	8	1475	24	1425	100	1025	8	T	172.0	165.4	3.0	9.1	15.3	C	-	40.4
									174.2	167.1	3.0	12.1	15.1	C	-	35.6 *

* Used for structural analysis.

a Followed by a water quench.

b L - longitudinal, T - transverse.

c Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

TABLE LX

MECHANICAL PROPERTIES OF ALLOY 334(10Mo-6Cr-2.5Al) AT 6" STAGE, DUPLEX (HIGH-LOW) ANNEAL PRIOR TO AGE, SAMPLES FROM BUTT END

Annealing Treatment				Age			Mechanical Properties							
High[a]		Low[a]					Tensile Properties						K_Q[c] ($ksi\sqrt{in}$)	
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Dirn.[b]	UTS (ksi)	YS (ksi)	El (%)	R/A (%)	E ($x10^6$ psi)	Break	LR	SR
1350	4	1200	4	900	96	L	157.9	150.4	18.0	36.2	16.9	B	161.5	-
							149.7	144.3	19.0	41.3	17.2	B	154.2	-
						T	153.9	151.0	10.0	26.7	15.8	C	-	82.9
							151.3	147.2	11.0	20.2	14.1	C	-	83.0*

a Followed by a water quench.

b L - longitudinal; T - transverse

c Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* Used for structural analysis.

TABLE LXI

MECHANICAL PROPERTIES OF ALLOY 227 (7Mo-4Cr-2.5Al) AT 6" STAGE, DUPLEX (HIGH-LOW) ANNEAL PRIOR TO AGE, SAMPLES FROM BUTT END

Annealing Treatment				Age			Mechanical Properties							
High[a]		Low[a]					Tensile						K_Q[c] (ksi$\sqrt{in}$)	
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Direction[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	LR	SR
1450	2	1250	4	950	8	L	148.9	144.9	23.0	56.5	16.4	C	186.1	-
							149.4	146.7	24.0	60.0	16.6	A	172.6	-
						T	149.2	145.8	10.0	45.4	16.6	A	-	86.2
							151.2	147.2	10.0	43.0	17.7	A	-	86.1*

[a] Followed by a water quench.

[b] L - longitudinal; T - transverse.

[c] Calculated from slow bend pre-cracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

* Used for structural analysis.

TABLE LXII

FURTHER MECHANICAL PROPERTIES OF ALLOY 334 (10Mo-6Cr-2.5Al) AT 6" STAGE DUPLEX (HIGH-LOW) ANNEAL PRIOR TO AGE, SAMPLES FROM BUTT END

Annealing Treatment				Age			Tensile Properties					
High[a]		Low[a]										
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Direction[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break
1350	4	1250	4	900	96	T	176.8	175.1	4.0	6.2	16.2	C
							178.4	173.1	4.0	4.8	16.5	A

[a] Followed by a water quench.

[b] L - longitudinal; T - transverse.

TABLE LXIII

FURTHER MECHANICAL PROPERTIES OF ALLOY 227 (7Mo-4Cr-2.5Al) AT 6" STAGE DUPLEX (HIGH-LOW) ANNEAL PRIOR TO AGE, SAMPLES FROM BUTT END

Annealing Treatment High[a] Temp. (F)	Annealing Treatment High[a] Time (hr)	Annealing Treatment Low[a] Temp. (F)	Annealing Treatment Low[a] Time (hr)	Age Temp. (F)	Age Time (hr)	Direction[b]	Tensile Properties UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break
1450	2	1325	8	950	8	T	155.9	153.9	-	-	15.4	OGM
							172.0	169.0	8.0	24.1	16.8	B
		1275	6			T	164.5	162.8	6.0	28.7	16.7	C
							172.3	167.4	3.0	10.0	16.1	C

[a] Followed by a water quench.
[b] L - longitudinal; T - transverse.

TABLE LXIV

HEAT TREATMENT OF SIX INCH BILLET

		Heat Treatment					
		Anneal					
		High[a]		Low[a]		Age[b]	
Alloy	Composition (bal. Ti)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Temp. (F)	Time (hr)
334	10Mo-6Cr-2.5Al	1350	4	1225	2	900	96
227	7Mo-4Cr-2.5Al	1450	2	1350	8	925	8
253	10Mo-8V-2.5Al	1350	4	1225	2	900	96

[a] Followed by WQ.

[b] Followed by AC.

TABLE LXV

ANTICIPATED* AND GOAL TRANSVERSE PROPERTIES AT CENTER OF SIX INCH DIAMETER BILLET

Alloy		UTS (ksi)	YS (ksi)	El (%)	RA (%)	K_{Ic} (ksi√in)
334	Anticipated:	165-170	160-165	5-8	12-18	62-68
	Goal:	182	171	12	18	60
227	Anticipated:	165-170	162-167	7-10	20-24	62-68
	Goal	186	169	12	18	60
253	Anticipated:	165-170	160-165	5-8	12-18	62-68
	Goal:	188	171	12	18	60

* Using the duplex anneal - aging sequence defined in Table LXIV.

TABLE LXVI

ROOM TEMPERATURE TENSILE PRECRACKED CHARPY TOUGHNESS AND FRACTURE TOUGHNESS PROPERTIES* OF SIX INCH BILLET OF ALLOY #334 (10Mo-6Cr-2.5Al)

		Mechanical Properties									
		Tensile						K_Q[c] (ksi√in.)		K_{Ic}[d] (ksi√in.)	
Location[a]	Direction[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	LR[e]	SL[e]	SR[e]	SL[e]
E	L	157.9	153.9	36.0	49.5	16.0	B	125.8	-		-
		158.4	154.8	34.0	56.5	16.7	C	141.0†	-		-
	T	158.9	151.5	10.0	22.3	15.4	A	-	59.3		
		155.2	148.8	20.0	24.3	15.6	C	-	58.6†		
M	L	150.9	150.6	32.0	45.3	15.9	B	129.2	-		-
		148.9	144.9	34.0	54.3	16.5	B	154.1	-		-
	T	157.7	149.4	25.0	29.6	15.5	C	-	64.6		
		159.0	150.0	25.0	29.9	15.9	A	-	61.1		
C	L	149.9	149.4	36.0	52.7	16.2	A	126.7	-	86.0	-
		147.3	145.2	34.0	46.1	15.3	A	123.9†			-
	T	154.9	147.9	28.0	35.2	15.6	C	-	68.5	-	68.9
		154.4	152.1	30.0	34.8	15.7	A		71.1†	-	69.3
		157.2	152.4	26.0	29.6	15.8	C	-		-	

* Duplex anneal 1350F - 4 hr. WQ plus 1225F - 2 hr. WQ and aged 900F - 96 hr. AC.

† Used for structural analysis.

a E: Edge
M: Mid-radius
C: Center

b L: Longitudinal
T: Transverse

c From slow bend precracked Charpy samples using $K_Q = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

d Valid fracture toughness, see Appendix H.

e For nomenclature used see Appendix F.

TABLE LXVII

ROOM TEMPERATURE TENSILE, PRECRACKED CHARPY TOUGHNESS AND FRACTURE TOUGHNESS PROPERTIES* OF SIX INCH BILLET OF ALLOY #227 (7Mo-4Cr-2.5Al)

Location[a]	Direction[b]	Mechanical Properties: Tensile UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	K_Q[c] (ksi√in.) LR[e]	SL[e]	K_{Ic}[d] (ksi√in.) SR[e]	SL[e]
E	L	182.1	168.7	12.0	40.0	16.0	B	58.5	-		-
		171.3	159.3	12.0	39.5	15.3	C	66.1†	-		-
	T	171.0	162.1	5.0	13.5	15.9	C	-	45.9		
		175.1	164.5	3.0	5.8	16.4	A	-	42.5†		
M	L	171.0	155.7	14.0	36.8	15.9	B	85.6	-		-
		171.0	155.7	14.0	35.6	16.2	C	77.8	-		-
	T	173.5	160.0	3.0	8.2	16.4	C	-	46.6		
		169.3	154.8	2.0	8.6	16.0	A	-	48.1		
C	L	169.5	153.3	10.0	33.4	15.9	C	80.4	-	55.2	-
		163.5	147.9	13.0	38.6	15.9	A	86.8†	-		-
	T	167.0	152.4	7.0	19.5	15.6	B	-	57.3	-	50.6
		166.0	151.0	7.0	15.7	15.9	C	-	41.8†	-	48.4

* Duplex annealed 1450F - 2 hr. WQ plus 1350F - 8 hr. WQ and aged 925F - 8 hr. AC.

† Used for structural analysis.

[a] E: Edge
M: Mid-radius
C: Center

[b] L: Longitudinal
T: Transverse

[c] From slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

[d] Valid fracture toughness, see Appendix H.

[e] For nomenclature used see Appendix F.

TABLE LXVIII

ROOM TEMPERATURE TENSILE PRECRACKED CHARPY TOUGHNESS AND FRACTURE TOUGHNESS PROPERTIES* OF SIX INCH BILLET OF ALLOY #253 (10Mo-8V-2.5Al)

		Mechanical Properties									
		Tensile						K_Q [c] (ksi√in.)		K_{Ic} [d] (ksi√in.)	
Location[a]	Direction[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	LR[e]	SL[e]	SR[e]	SL[e]
E	L	157.6	152.4	16.0	51.9	15.8	B	143.8	-		-
		150.9	147.9	14.0	48.9	15.9	C	129.7†	-		-
	T	153.4	145.8	10.0	15.7	15.3	B	-	89.1		
		154.7	147.9	10.0	19.9	15.0	C	-	72.6†	-	
M	L	143.9	143.1	17.0	63.2	15.9	C	123.3	-		-
		148.4	147.0	17.0	54.3	16.3	C	123.0	-		-
	T	156.7	145.8	8.0	19.9	15.3	A	-	71.5		
		154.9	144.9	8.0	20.0	15.8	A	-	83.4		
C	L	148.4	143.4	13.0	53.3	15.6	C	116.7†	-	80.1	-
		146.1	141.9	15.0	49.9	15.1	C	128.0	-		-
	T	155.8	147.3	8.0	16.8	15.6	B	-	80.0	-	75.1
		153.6	144.7	8.0	22.3	15.0	C	-	71.8†	-	84.9
		157.9	147.9	8.0	18.5	15.5	A	-		-	

* Duplex annealed 1350F - 4 hr. WQ plus 1225F - 2 hr. WQ and aged 900F - 96 hr. AC.

† Used for structural analysis.

a E: Edge
M: Mid-radius
C: Center
See Figure

b L: Longitudinal
T: Transverse

c From slow bend precracked Charpy samples using

$$K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$$

d Valid fracture toughness , see Appendix H.

e For nomenclature used see Appendix F.

TABLE LXIX

ROOM AND ELEVATED TEMPERATURE TENSILE PROPERTIES
Alloy 334(10Mo-6Cr-2.5Al), Six Inch Billet*

Temperature	Billet[a] Location	Direction[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break
74F	E	L	157.9	153.9	36.0	49.5	16.0	B
			158.4	154.8	34.0	56.5	16.7	C
		T	158.9	151.5	10.0	22.3	15.4	A
			155.2	148.8	20.0	24.3	15.6	C
	M	L	150.9	150.6	32.0	45.3	15.9	B
			148.9	144.9	34.0	54.3	16.5	B
		T	157.7	149.4	25.0	29.6	15.5	C
			159.0	150.0	25.0	29.9	15.9	A
	C	L	149.9	149.4	36.0	52.7	16.2	A
			147.3	145.2	34.0	46.1	15.3	A
		T	154.9	147.9	28.0	35.2	15.6	C
			154.4	152.1	30.0	34.8	15.7	A
			157.2	152.4	26.0	29.6	15.8	C
400F	E	L	-	-	-	-	-	-
		T	134.7	125.3	8.0	27.1	15.5	B
	M	L	127.3	120.2	18.0	59.7	15.6	B
		T	133.3	124.4	15.0	47.6	15.3	B
	C	L	129.7	120.7	20.0	62.3	15.6	B
		T	128.7	119.9	14.0	38.3	15.3	C
			128.9	122.6	16.0	52.3	15.0	C
800F	E	L	119.7	106.2	20.0	69.4	13.7	C
		T	120.7	107.4	11.0	31.0	13.9	B
			111.5	100.2	8.0	28.4	13.3	C
	M	L	118.0	105.4	23.0	73.2	13.5	B
		T	114.8	103.0	9.0	31.3	13.0	A
			118.1	104.8	13.0	36.2	13.5	A
	C	L	115.3	103.3	20.0	73.6	13.7	A
		T	115.5	103.8	11.0	40.4	13.2	B
			114.9	103.5	13.0	46.5	13.7	B

* Duplex anneal 1350F - 4 hr. WQ plus 1225F - 2 hr. WQ and aged 900F - 96 hr. AC.

[a] E: Edge
M: Mid-radius
C: Center

[b] L: Longitudinal
T: Transverse

TABLE LXX

ROOM AND ELEVATED TEMPERATURE TENSILE PROPERTIES
Alloy 227 (7Mo-4Cr-2.5Al), Six Inch Billet*

Temperature	Billet[a] Location	Direction[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break
70F	E	L	182.1	168.7	12.0	40.0	16.0	B
			171.3	159.3	12.0	39.5	15.3	C
		T	171.0	162.1	5.0	13.5	15.9	C
			175.1	164.5	3.0	5.8	16.4	A
	M	L	171.0	155.7	14.0	36.8	15.9	B
			171.0	155.7	14.0	35.6	16.2	C
		T	173.5	160.0	3.0	8.2	16.4	C
			169.3	154.8	2.0	8.6	16.0	A
	C	L	169.5	153.3	10.0	33.4	15.9	C
			163.5	147.9	13.0	38.6	15.9	A
		T	167.0	152.4	7.0	19.5	15.6	B
			166.0	151.0	7.0	15.7	15.9	C
400F	E	L	-	-	-	-	-	-
		T	145.7	120.7	12.0	38.6	15.7	B
	M	L	141.6	114.1	13.0	52.7	15.2	C
		T	143.1	115.9	8.0	29.6	15.1	C
	C	L	136.1	107.0	18.0	69.1	14.9	C
		T	138.0	110.7	11.0	30.4	15.1	C
			132.8	109.5	14.0	52.7	14.6	C
			142.9	116.4	10.0	40.1	15.1	B
800F	E	L	123.8	91.9	16.0	65.6	13.3	C
		T	126.9	91.3	8.0	19.0†	13.9	B
			124.7	98.1	10.0	40.4	13.5	B
	M	L	125.8	90.5	20.0	73.6	13.4	B
		T	123.6	88.5	10.0	26.7	13.0	C
			123.6	90.9	8.0	43.8	13.8	B
	C	L	122.9	89.3	17.0	72.4	13.1	C
		T	119.2	83.9	16.0	42.2	12.8	A
			122.6	86.7	12.0	42.6	13.2	C

* Duplex annealed 1450F - 2 hr. WQ + 1350F - 8 hr. WQ and aged 925F - 8 hr. AC.

† Double neck.

[a] E: Edge
M: Mid-Radius
C: Center

[b] L: Longitudinal
T: Transverse

TABLE LXXI

ROOM AND ELEVATED TEMPERATURE TENSILE PROPERTIES Alloy 253(10Mo-8V-2.5Al), Six Inch Billet*

Temperature	Billet[a] Location	Direction[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break
74F	E	L	157.6	152.4	16.0	51.9	15.8	B
			150.9	147.9	14.0	48.9	15.9	C
		T	153.4	145.8	10.0	15.7	15.3	B
			154.7	147.9	10.0	19.9	15.0	C
	M	L	143.9	143.1	17.0	63.2	15.9	C
			148.4	147.0	17.0	54.3	16.3	C
		T	156.7	145.8	8.0	19.9	15.3	A
			154.9	144.9	8.0	20.0	15.8	A
	C	L	148.4	143.4	13.0	53.3	15.6	C
			146.1	141.9	15.0	49.9	15.1	C
		T	155.8	147.3	8.0	16.8	15.6	B
			153.6	144.6	8.0	22.3	15.0	C
			157.9	147.9	8.0	18.5	15.5	A
400F	E	L	-	-	-	-	-	-
		T	122.0	113.6	8.0	33.9	15.3	B
	M	L	121.5	117.3	18.0	64.4	15.0	B
		T	131.2	118.3	15.0	45.3	15.0	C
	C	L	118.1	111.0	14.0	69.1	15.5	C
		T	128.2	115.2	12.0	36.2	15.0	B
			129.2	117.3	13.0	48.3	15.1	B
800F	E	L	106.4	93.1	18.0	64.0	13.4	B
		T	109.5	96.0	10.0	44.1	13.3	C
			109.2	96.6	14.0	52.7	14.0	B
	M	L	106.2	93.8	19.0	69.5	13.2	B
		T	111.2	96.0	14.0	44.1	14.1	C
			111.3	97.3	15.0	52.1	13.2	A
	C	L	106.2	93.8	15.0	61.1	13.8	A
		T	113.3	98.1	11.0	43.5	13.9	C
			110.2	95.6	12.0	46.7	13.4	B

* Duplex annealed 1350F - 4 hr. WQ + 1225F - 2 hr. WQ and aged 900F - 96 hr. AC.

a E: Edge
M: Mid-Radius
C: Center

b L: Longitudinal
T: Transverse

TABLE LXXII

ROOM TEMPERATURE TENSILE AND PRECRACKED CHARPY TOUGHNESS PROPERTIES* OF 6" BILLET OF ALLOY #334(10Mo-6Cr-2.5Al)

		Mechanical Properties							
		Tensile						K_Q[c] ($ksi\sqrt{in}$)	
Location[a]	Direction[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	LR[d]	SL[d]
E	L	151.6	148.8	36.0	46.5	17.5	B		--
	T	154.4	149.7	21.0	30.0	15.6	C	--	
M	L	138.6	136.1	34.0	53.4	15.9	B	156.1	--
								143.4	--
	T	151.6	150.0	24.0	28.4	16.4	B	--	82.2
									66.2
C	L	148.3	144.3	32.0	37.7	16.4	B		--
	T	147.1	144.6	25.0	33.1	15.6	B	--	78.2
		151.8	147.6	28.0	35.0	15.9	A	--	72.2

* Duplex annealed 1350F - 4 hr WQ plus 1225F - 2 hr WQ and aged 1000F - 96 hr AC.

[a] E: Edge
M: Mid-radius
C: Center

[b] L: Longitudinal
T: Transverse

[c] From slow bend precracked Charpy samples using $K_Q = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

[d] For nomenclature used see Appendix F.

TABLE LXXIII

ROOM TEMPERATURE TENSILE AND PRECRACKED CHARPY TOUGHNESS PROPERTIES* OF 6" BILLET OF ALLOY #227 (7Mo-4Cr-2.5Al)

		Mechanical Properties							
		Tensile						K_Q[c] ($ksi\sqrt{in}$)	
Location[a]	Direction[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	LR[d]	SL[d]
E	L	164.0	156.9	14.0	38.0	16.1	A		--
	T	164.5	153.9	4.0	9.7	16.5	A	--	
M	L	162.0	151.2	14.0	39.8	16.0	A	102.2	--
								99.6	
	T	158.8	149.1	-	-	15.9	OGM	--	55.3
									58.0
C	L	158.5	147.6	16.0	46.5	15.8	C		--
	T	155.3	144.9	8.0	29.0	15.9	C	--	62.2
		158.3	148.8	10.0	30.7	16.0	A	--	60.1

* Duplex annealed 1450F - 2 hr WQ plus 1350F - 8 hr WQ and aged 1000F - 8 hr AC

[a] E: Edge
M: Mid-radius
C: Center

[b] L: Longitudinal
T: Transverse

[c] From slow bend precracked Charpy samples using $K_Q = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

[d] For nomenclature used see Appendix F.

TABLE LXXIV

ROOM TEMPERATURE TENSILE AND PRECRACKPED CHARPY TOUGHNESS PROPERTIES* OF 6" BILLET OF ALLOY #253(10Mo-8V-2.5Al)

		Mechanical Properties							
		Tensile						K_Q[c] ($ksi\sqrt{in}$)	
Location[a]	Direction[b]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	LR[d]	SL[d]
E	L	142.6	137.9	16.0	47.7	15.6	C		--
		144.9	140.3	18.0	60.4	15.8	C		--
	T	143.4	137.3	10.0	27.0	14.9	B	--	
M	L	149.8	147.6	19.0	48.4	15.5	C	145.9	--
								140.0	
	T	148.9	139.7	11.0	29.6	15.1	C	--	78.1
									73.8
C	L	139.8	135.8	16.0	47.7	14.9	C		--
	T	144.9	139.7	11.0	27.6	15.0	B	--	83.5
		145.4	140.6	10.0	27.6	15.0	C	--	78.9

* Duplex annealed 1350F - 4 hr WQ plus 1225F - 2 hr WQ and aged 1000F - 96 hr AC.

[a] E: Edge
M: Mid-radius
C: Center

[b] L: Longitudinal
T: Transverse

[c] From slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

[d] For nomenclature used see Appendix F.

TABLE LXXV

ROOM TEMPERATURE TENSION-TENSION FATIGUE DATA

(Six Inch Diameter Billet, Transverse Specimens Center Location)

Unnotched, R = + 0.1

Maximum Stress ksi	Cycles to Failure, x10³ Alloy 334 [a]	Alloy 227 [b]	Alloy 253 [c]
120	-	217	-
115	-	1,337	-
110	-	2,542*	-
110	-	2,640*	48
105	-	-	44
105	-	-	44
100	2,737	2,614*	2,524*
100	1,915	2,676*	6,829*
95	618	-	3,073*
95	2,653*	-	-
90	2,448	-	-
90	2,544*	-	-

Notched, K_t = 3.0, R = + 0.1

Maximum Stress ksi	Alloy 334	Alloy 227	Alloy 253
52		510	
50	35	2,568*	
48		-	44
47	101	6,891*	-
45	2,603*		-
43			125
40			2,614*

Tensile Properties, Transverse Specimens Center/Mid-Radius Positions

	Alloy 334	Alloy 227	Alloy 253
UTS, ksi	156	167	156
YS, ksi	151	152	147
% Elongation	28	7	8
% RA	33	18	19

[a] (10Mo-6Cr-2.5Al) - Duplex annealed 1350F - 4 hr, WQ + 1225F - 2 hr, WQ, aged 900F - 96 hr.

[b] (7Mo-4Cr-2.5Al) - Duplex annealed 1450F - 2 hr, WQ + 1350F - 8 hr, WQ, aged 925F - 8 hr.

[c] (10Mo-8V-2.5Al) - Duplex annealed 1350F - 4 hr, WQ + 1225F - 2 hr, WQ, aged 900F - 96 hr.

* Test discontinued, no failure.

TABLE LXXVI

CREEP AND CREEP STABILITY FROM CENTER LOCATION 6 INCH BILLET TENSILE SAMPLES - ALLOY 334(10Mo-6Cr-2.5Al), 227(7Mo-4Cr-2.5Al) AND 253(10Mo-8V-2.5Al)

Alloy	Creep Exposure[c] Temp. (F)	Creep Exposure[c] Time (hr)	Creep Exposure[c] Stress (ksi)	Total Creep Strain (%)	Direction	Tensile Properties[d] UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break
334 [a]	No exposure			-	L	148.6	147.3	35.0	49.4	15.8	
	600	100	100	0.249		150.9	149.4	18.0	46.5	17.1	B
	No exposure				T	155.5	150.8	28.0	33.2	15.7	
	600	100	100	0.920		151.6	145.8	8.0	29.7	16.3	B
				0.440P		155.8	151.5	10.0	17.6	15.8	A
227 [b]	No exposure			-	L	166.5	150.6	11.5	36.0	15.9	
	600	100	100	0.984		160.3	155.5	14.0	46.8	14.2	A
	No exposure			-	T	166.5	151.7	7.0	16.6	15.8	
	600	100	100	0.424		169.4	165.8	5.0	10.1	15.4	A
				0.640P		173.5	164.5	3.0	11.7	15.5	A
253 [a]	No exposure			-	L	147.3	142.7	14.0	51.6	15.4	
	600	100	100	0.298		150.9	147.9	15.0	49.9	16.0	C
	No exposure			-	T	150.8	146.7	8.0	19.2	15.3	
	600	100	100	0.040		158.7	153.9	6.0	16.5	14.8	B
				1.30P		155.8	151.5	9.0	17.6	15.9	B

[a] Duplex annealed 1350F-4 hr WQ + 1225F - 2 hr WQ, aged 900F - 96 hr AC.

[b] Duplex annealed 1450F - 2 hr WQ + 1350F - 8 hr WQ, aged 925F - 8 hr AC.

[c] In air, samples indicated P after creep strain pickled prior to tensile testing, other samples tested with skin on.

[d] No exposure sample results are average values taken from Tables LXVI, LXVII and LXVIII.

TABLE LXXVII

ALLOY #334 (10Mo-6Cr-2.5Al) PHASE III MECHANICAL PROPERTY DATA,* Half Inch Plate

Annealing[a] Treatment		Aging[b] Treatment			Mechanical Properties						K_Q[d] (ksi$\sqrt{\text{in.}}$)	
					Tensile Properties							
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Direction[c]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	RW	WR
1350	8	950	96	L	178.1	175.4	8.0	19.9	15.2	B	53.6	-
					181.4	178.9	8.0	18.2	15.3	A	49.2	-
				T	197.4	191.8	2.0	3.2	15.6	A	-	45.1
					198.9	190.9	2.0	5.6	16.6	C	-	44.4
		1025	96	L	160.6	160.5	14.0	29.2	14.8	B	65.1	-
					159.0	157.5	12.0	42.2	16.1	C	64.7	-
				T	180.4	173.4	6.0	9.4	17.6	A	-	60.0†
					176.9	168.0	4.0	7.8	16.8	B	-	60.1

* Material forged to 10.5 inch RCS then rolled from 3 to 1/2 inch plate from 1500F (four re-heats: 2 inch, 1-3/8 inch, 0.9 inch, 0.7 inch), finished at ~1225F.

† Used for structural analysis.

[a] Followed by WQ.

[b] Followed by AC.

[c] L - longitudinal
T - transverse

[d] Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

TABLE LXXVIII

ALLOY #227 (7Mo-4Cr-2.5Al) PHASE III MECHANICAL PROPERTY DATA,* Half Inch Plate

Annealing[a] Treatment		Aging[b] Treatment			Mechanical Properties							
					Tensile Properties						K_Q[d] (ksi$\sqrt{\text{in.}}$)	
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Direction[c]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	RW	WR
1450	8	1025	8	L	170.3	164.4	12.0	62.3	14.8	C	45.3	-
					171.4	163.2	14.0	31.9	15.3	B	50.4	-
				T	184.7	176.2	13.0	32.3	15.9	B	-	42.7
					184.9	179.8	9.0	31.3	15.9	C	-	42.4†
		1125	8	L	147.1	143.1	19.0	51.6	16.3	A	98.5	-
					145.3	142.8	17.0	48.5	15.0	A	94.4	-
				T	155.9	150.0	12.0	44.2	16.8	B	-	83.0
					154.6	149.7	18.0	35.7	17.0	C	-	83.2

* Material forged to 10.5 inch RCS then rolled from 2-3/4 to 1/2 inch plate from 1500F (two re-heats 1-3/8 and 0.9 inch), finished at ~1250F.

† Used for structural analysis.

a Followed by WQ.

b Followed by AC.

c L - longitudinal
T - transverse

d Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

TABLE LXXIX

ALLOY #253 (10Mo-8V-2.5Al) PHASE III MECHANICAL PROPERTY DATA,* Half Inch Plate

Annealing[a] Treatment		Aging[b] Treatment			Mechanical Properties							
					Tensile Properties						K_Q[d] (ksi√in.)	
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Direction[c]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	RW	WR
1350	8	950	96	L	180.1	170.8	6.0	7.4	14.6	A	47.5	-
					176.2	168.4	4.0	5.4	15.1	B	50.4	-
				T	190.1	184.1	5.0	10.5	15.3	B	-	47.0
					187.4	179.6	7.0	18.5	14.4	B	-	46.2†
		1025	96	L	160.1	156.6	4.0	6.6	14.7	B	63.8	-
					155.9	153.0	4.0	4.4	14.3	B	59.9	
				T	166.7	160.6	8.0	14.3	14.5	B	-	62.2
					169.6	164.1	6.0	13.0	15.8	C	-	58.8

* Material forged to 10.5" RCS then rolled from 3-3/8" to 1/2" plate from 1500F (two reheats, 1-3/4" and 1-1/8") finished at ~1250F.

† Used for structural analysis.

[a] Followed by WQ.

[b] Followed by AC.

[c] L - longitudinal
T - transverse

[d] Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

TABLE LXXIX

ALLOY #253 (10Mo-8V-2.5Al) PHASE III MECHANICAL PROPERTY DATA,*
Half Inch Plate

Annealing[a] Treatment		Aging[b] Treatment			Mechanical Properties							
					Tensile Properties						K_Q[d] (ksi√in.)	
Temp. (F)	Time (hr)	Temp. (F)	Time (hr)	Direction[c]	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	RW	WR
1350	8	950	96	L	180.1	170.8	6.0	7.4	14.6	A	47.5	-
					176.2	168.4	4.0	5.4	15.1	B	50.4	-
				T	190.1	184.1	5.0	10.5	15.3	B	-	47.0
					187.4	179.6	7.0	18.5	14.4	B	-	46.2†
		1025	96	L	160.1	156.6	4.0	6.6	14.7	B	63.8	-
					155.9	153.0	4.0	4.4	14.3	B	59.9	
				T	166.7	160.6	8.0	14.3	14.5	B	-	62.2
					169.6	164.1	6.0	13.0	15.8	C	-	58.8

* Material forged to 10.5" RCS then rolled from 3-3/8" to 1/2" plate from 1500F (two reheats, 1-3/4" and 1-1/8") finished at ~1250F.

† Used for structural analysis.

[a] Followed by WQ.

[b] Followed by AC.

[c] L - longitudinal
T - transverse

[d] Calculated from slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$

TABLE LXXX

BETA MATRIX TEXTURE STUDY FOR PHASE III BILLET AND PLATE

Alloy	Product Form [a]	Heat Treatment[b] I Temp. (F)	I Time (hr)	II Temp. (F)	II Time (hr)	Sample Orientation[c]	Poles Investigated [d] (110)	(200)	(211)
334	B	1350	4	1225	2	LS	X	X	X
						RS	X	X	-
	P	1350	8	-	-	RW	X	X	-
227	B	1450	2	1350	8	RS	X	X	-

[a] B - Billet
P - Plate

[b] Both anneals followed by WQ.

[c] See Appendix F for nomenclature used. Letters indicate plane of material analyzed.

[d] 45° one quadrant figures.

TABLE LXXXI

MECHANICAL PROPERTIES AND DUCTILITY DIRECTIONALITY OF ALLOYS 334(10Mo-6Cr-2.5Al) and 227(7Mo-4Cr-2.5Al) BILLET AS DUPLEX ANNEALED*

		Mechanical Properties							Ductility Directionality					
									Reduction in Diameter[a] (inch x 10^{3})					
												Average		
Alloy	Direction	UTS (ksi)	YS (ksi)	El (%)	RA (%)	E ($x10^6$ psi)	Break	Average RA(%)	L	S_1	S_2	L	S_1	S_2
334	L	135.7	128.7	22.0	53.5	13.9	B		-	077	078			
		135.3	129.3	22.0	54.5	14.8	C		-	090	070			
		135.5	129.0	22.0	45.0	16.2	A		-	052	067			
		137.3	129.3	24.0	55.7	14.9	A	52.2	-	083	078	-	076	073
	T	137.8	132.8	18.0	48.3	14.5	B		073	060	-			
		135.5	131.0	16.0	38.7	13.6	B		054	054	-			
		127.3	126.3	11.0	46.7	13.0	A		070	057	-			
		138.8	135.3	16.0	43.7	14.4	A†	44.4	088	060	-	071	058	-
227	L	125.5	123.2	22.0	55.7	12.7	B		-	109	065			
		123.5	121.1	22.0	56.1	14.7	B		-	083	075			
		123.5	120.2	20.0	61.1	13.9	B		-	095	101			
		125.2	123.2	17.0	58.7	13.4	B	57.9	-	075	099	-	091	085
	T	128.0	124.1	12.0	47.9	14.5	B		082	048	-			
		129.0	125.5	12.0	53.2	14.5	B†		087	064	-			
		127.8	123.2	14.0	49.7	13.1	A		078	060	-			
		127.3	123.2	20.0	45.5	14.2	A	49.1	066	052	-	078	056	-

* Alloy #334: 1350F - 4 hr WQ plus 1225F - 2 hr WQ.
Alloy #227: 1450F - 2 hr WQ plus 1350F - 8 hr WQ.

† Used for structural study.

a L - longitudinal axis of billet.
S_1, S_2 - transverse axis of billet
Values represent reduction in diameter of original 0.250" round in the directions specified.

TABLE LXXXII

PHASE III STRUCTURAL WORK: SAMPLE GROUPS EVALUATED

Group		Figures
1	Single/double aged (pre-age)	94-102
2	"Optimum" processing 10.5" RCS→6" billet	103-128
3	Beta recrystallized	129-138
4	Beta processed	139-147
5	High-low solution anneal	148-154
6	Low-high solution anneal	155-162
7	Six inch billet	163-204
8	Half inch plate	205-213
9	Tensile samples	214-221
10	Billet as duplex solution annealed	222-227

TABLE LXXXIII

MECHANICAL PROPERTIES AND CORRESPONDING MICROSTRUCTURAL FEATURES

			Mechanical Properties				Microstructural Features										
												SEM Dimple Size (μm)[g]		Particle Spacing(μm)		Crack Path Dimple Size (μm)[g]	
Gp.[a]	Spec. Code[b]		Dirn.	YS (ksi)	RA (%)	K_Q ksi $\sqrt{in.}$	Str. α[c]	Prim. α Aspect Ratio[d]	Sub-Grn.[c]	Grain Bdry. α[e]	Frct. Path[f]	Small	Large	Fine	Prim.	Small	Large
1	4C1Y1	C	L	186	23	86 (LR)	P	6	-	SC	3	?	10	-	-	-	-
	4C1Z1	C	L	190	17	69 (LR)	P	6	-	SC	3	1.5	10	-	-	-	-
	3C3Y1	C	L	157	33	104 (LR)	P	5	-	-	1	1.5	7	-	-	-	-
	3C3Z1	C	L	170	22	75 (LR)	P	6	-	-	2	2	10	-	-	-	-
2	4ELR10	C	L	183	15	84 (LR)	P	6	-	SC	2	2	8	0.2	4	2	12
	4ESR2	C	T	185	4	57 (SR)	P	6	-	SC	3	1.5	10	0.2	2	3	15
	7ELR11	C	L	174	24	59 (LR)	P	6	P	NP	1	1.5	20	0.2	7	3	10
	7ESR3	C	T	171	12	51 (SR)	P	6	P	NP	2	1.5	20	0.2	6	3	15
	7ELR9	C	L	183	28	78 (LR)	P	3	P	SC	2	-	-	0.2	5	4	15
	7ESR1	C	T	183	6	41 (SR)	P	3	P?	SC	3	-	-	0.2	4	3	10
	3ELR10	C	L	172	31	78 (LR)	P	6	NP?	SC	2	2	8	0.2	1.5	3	15
	3ESR2	C	T	167	13	48 (SR)	P	6	NP?	SC	3	2	10	0.2	2	3	15
3	4MSL8	C	L	167	14	58 (LR)											
			T	178	6	45 (SL)	NP	6	NP	C	3.5	3	20	0.2	3	3	6
	7MSL4	C	L	180	5	57 (LR)											
			T	188	6	41 (SL)	NP	6	NP	C	3.5	2	15	0.2	10	3	10
4	4SL2	C	L	177	13	99 (LR)											
			T	182	9	60 (SL)	P	6	P?	SC	3	1.5	12	0.2	2	3	10
	7SL2	C	L	183	13	53 (LR)											
			T	184	10	57 (SL)	P	6	NP?	SC	2	1.5	10	0.2	6	3	15
5	4SR12	C	L	147	39	158 (LR)											
			T	149	23	83 (SR)	P	3	NP?	SC	3	-	-	0.4	1.5	3	15
	7SR22	C	L	146	58	179 (LR)											
			T	146	44	86 (SR)	P	3	NP?	SC/G	3	-	-	0.5	3	3	15
6	4SR16	C	L	167	31	95 (LR)											
			T	170	6	60 (SR)	P	3	NP?	SC/G	3	3	15	0.4	4	4	10
	7SR20	C	L	-	-	- (LR)											
			T	166	11	38 (SR)	P	2	P	SC/G	3	1.0	8	0.2	6	5	15
7	4LRC2	C	L	147	50	126 (LR)	P	3	NP?	SC/G	3	2.0	15	0.5	1.5	3	10
	4SLC2	C	T	151	33	70 (SL)	P	2	NP?	SC/G	2	2.0	20	0.5	1.5	3	10
	4SLC4	C	L	144	37	- (LR)											
			T	146	34	75 (SL)	P	2	NP?	SC/G	2	1.5	10	0.5	2	2.5	10
	4LRE2	C	L	155	53	134 (LR)	P	6	NP?	SC	3	-	-	0.4	1.5	3	12
	4SLE2	C	T	150	23	59 (SL)	P	3	NP?	SC	2	-	-	0.4	1.5	2.5	10
	7LRC2	C	L	151	36	84 (LR)	P	5	NP	SC/G	2	3	8	0.3	3	2.5	8
	7SLC1	C	T	152	18	50 (SL)	P	5	NP?	SC/G	2	3	12	0.2	2	3	12
	7LRE2	C	L	164	40	62 (LR)	P	6	NP?	SC/G	3	-	-	0.3	3	3	10
	7SLE2	C	T	163	10	44 (SL)	P	5	P?	SC/G	3	-	-	0.2	2.5	3	8
	3LRC1	C	L	143	52	123 (LR)	P	5	P?	SC/G	3	2	8	0.3	1.5	2	12
	3SLC2	C	T	147	19	76 (SL)	P	6	NP?	SC/G	2	2	15	0.4	1.5	2	10
	3LRE2	C	L	150	51	137 (LR)	P	5	NP?	SC/G	3	-	-	0.4	1.0	2	8
	3SLE2	C	T	147	18	81 (SL)	P	6	NP?	SC/G	2	-	-	0.4	1.0	2	10
8	4WRH1	C	L	159	36	65 (RW)											
			T	171	9	60 (WR)	P	3	NP?	SC/G	2	-	-	0.3	6	3	15
	7WRL2	C	L	164	47	48 (RW)											
			T	178	32	43 (WR)	P/NP	2	P	SC/G	1	-	-	0.3	6	4	10
	3WRL2	C	L	170	6	49 (RW)											
			T	182	15	47 (WR)	P	4	P?	SC/L	2	-	-	0.3	5	4	8
9	4TC2	T	L	147	50	-					2 (L)	2	12	-	2	4	10
			T	151	33	-	P	3	NP?	SC/G	3 (R)						
	7ET3	T	L	174	24	-					2 (L)	1.5	20?	-	6	4	10
			T	171	12	-	P	6	P	NP	2 (R)						
	7MT7	T	L	180	5	-					3.5(L)	2	8	-	-	-	-
			T	188	6	-	NP	6	NP	C	3.5(R)						
10	4T4	T	L	129	52	-					2 (L)	-	-	-	1.5	3	12
			T	131	44	-	P	3	NP?	SC/G	3 (S_1)	-	-	-	1.5	3	10
	7T2	T	L	122	58	-					3 (L)	-	-	-	2	3	8
			T	124	49	-	P	5	NP?	SC/G	3 (S_1)	-	-	-	3	2	10

[a] See Table LXXXII
[b] C - Charpy; T - Tensile
[c] P - Present; NP - Not Present
[d] Approximate average value
[e] C - Continuous grain boundary alpha; SC - Semi-continuous grain boundary alpha
SC/G - Semi-continuous but mainly of a globular type; NP - Not Present
[f] 1 - Predominantly Transgranular; 4 - Predominantly Intergranular/Along Stringer Alpha Particles (crack branching)
[g] Large dimple size was made up of groups of smaller dimples

TABLE LXXXIV

MECHANICAL PROPERTIES OF SAMPLES USED FOR STRUCTURAL ANALYSIS AFTER A DUPLEX (LOW-HIGH)* AGING TREATMENT

Alloy No.	Sample Code	Treatment: Solution Treat Temp. (F)	Solution Treat Time (hr)	Age Temp. (F)	Age Time (hr)	Age Temp. (F)	Age Time (hr)	Properties[a] YS	RA	K_Q[b]
334	4C1Y1	1350	4	-	-	900	96	186	23	86
	4C1Z1	1350	4	750	8	925	8	190	17	69
253	3C3Y1	1275	4	-	-	950	96	157	33	104
	3C3Z1	1275	4	750	8	900	8	170	22	75

* Low to produce phase separation of solute lean bcc "zones," high to transform these regions to a fine dispersion of α-phase.

[a] Average of two tests in each case.

[b] From slow bend precracked Charpy samples using $K_Q^2 = \frac{W}{A} \times \frac{E}{2(1-\nu^2)}$.

TABLE LXXXV

FORGEABILITY OF THE PHASE III ALLOYS

Alloy No.	Composition (bal. Ti)	Bloom Sample Location	Average Compressive Flow Stress, x 10^3 psi[a,b] 1450F	1550F	1650F
334	10Mo-6Cr-2.5Al	Edge	95	85	-
		Center	87	76	-
227	7Mo-4Cr-2.5Al	Edge	-	61	55
		Center	-	64	54
253	10Mo-8V-2.5Al	Edge	76	68.5	-
		Center	74	68.5	-
-	6Al-4V	-	92	75	70
beta III	11.5Mo-6Zr-4.5Sn	-	73	-	63

[a] Compressive flow stress = $\dfrac{\text{Work}}{\text{Volume X } L_N \dfrac{(H_i)}{(H_f)}}$

[b] Strain rate approximately 275 sec^{-1}

TABLE LXXXVI

ENDURANCE LIMIT OF CONTRACT ALLOYS[@], AND COMPARISON WITH OTHER POTENTIAL DEEP HARDENABLE TITANIUM ALLOYS

Alloy	UTS (ksi)	Endurance Limit (ksi) Unnotched	Endurance Limit (ksi) Notched	Endurance Limit/UTS (%) Unnotched	Endurance Limit/UTS (%) Notched
334	156	92	46	59	29.5
227	167	114	51	68	30.5
253	156	104	42	67	27
Ti-6-22-22S*	171	95	45	55	26
Ti-6Al-2Sn-4Zr-6Mo†	169/186	81	36	<48	<21

@ Six inch diameter billet, transverse specimens center locatic[illegible] = +0.1, K_t (notched) = 3.0, 2.5×10^6 cycles, values [illegible]om Figures 230, 231 and 232.

* Two inch bar, longitudinal specimens mid-radius location, R = +0.1, K_t(notched) = 3.0, 10^7 cycles, Table XXXIII reference 27.

† Forgings, references 40 and 41.

TABLE LXXXVII

TOUGHNESS-DUCTILITY OF Ti-Mo-Cr-V-Al HALF INCH PLATE ALLOYS[†] AT GOAL YIELD STRENGTH LEVEL[@]

Alloy No.	Composition (bal Ti) Mo	Cr	V	Al	K_Q[a] (ksi√in) RW	WR	RA[b] (%) L	T
334	10	6	-	2.5	57.0	59.9	24.7	8.5
16*	8	4.5	-	2.5	55.0	62.5	24.5	20.0
227	7	4	-	2.5	42.5	55.0	46.7	25.1
253	10	-	8	2.5	48.0	55.2	4.7	15.0

@ At a yield strength corresponding to YS/density of 1.0 x 10^6 inches.

† Processed in a similar manner; i.e, low temperature processed, annealed at $\sim\beta$ T - 75F for 8 hours.

* Data developed under NAVAIR contract N00019-73-C-0335, alloy composition derived on basis of Phase I and II results under present contract.

a From Figures 234, 235, 236 and 237.

b From Figures 238, 239, 240 and 241.

TABLE LXXXVIII

PREDICTED DUCTILITY DIRECTIONALITY BASED ON THE ANTICIPATED CRACK CHARACTERISTICS IN PLATE AND BILLET*

Product Form	Direction[a]		Crack Characteristics		Predicted Ductility
	Tensile Axis	Crack Propagation	Nucleation[b]	Growth[c]	
Billet	L	S_1 or S_2	D	L	High
	S_2	L	E	L	Moderate
	S_2	S_1	D	S	Low
Plate	R	W	E/D	L	Mod-High
	R	T	D	L	High
	W	R	E	L	Moderate
	W	T	D	S	Low

* See Figures 259 and 260 .

[a]See Appendix F.
Billet L - longitudinal
S_1,S_2 - transverse
Plate R - rolling direction
W - width
T - thickness

[b] D - Difficult nucleation
E - Easy nucleation
} See text.

[c] L - Large amount of plastic work during deformation.
S - Small amount of plastic work during deformation.

TABLE LXXXIX

TRANSVERSE MECHANICAL PROPERTIES OF CONTRACT ALLOYS IN SIX INCH SECTION BILLET

Alloy No.	Composition (bal. Ti)	Center Six Inch Billet[a] YS (ksi)	El (%)	RA (%)	K_{Ic} (ksi√in)	$(K_{Ic}/YS)^2$ (inches)	Predicted from Alloy Trend Line[b] YS (ksi)	El (%)	RA (%)	K_{Ic} (ksi√in)	$(K_{Ic}/YS)^2$ (inches)
	Contract Goal[c]	-	-	-	-	-	-	12	18	60	0.095
334	10Mo-6Cr-2.5Al	150.8	28.0	33.2	69.1	0.210	171*	15	19	60	0.119
227	7Mo-4Cr-2.5Al	151.7	7.0	17.6	49.5	0.123	169*	3	15	46	0.074
253	10Mo-8V-2.5Al	146.6	8.0	19.2	80.0	0.300	171*	5	13	58	0.115

a Actual values from center of six inch section, heat treated as specified in Tables LXVI (#334), LXVII (#227) and LXVIII (#253).

b Values predicted at goal yield strength level from Figures 248, 251 and 254 (#334), 249, 252 and 255 (#227), and 250, 253 and 256 (#253).

c Contract goal at a yield strength corresponding to YS/density of 1.0 x 10^6 inches.

* Contract goal yield strength level (density normalized).

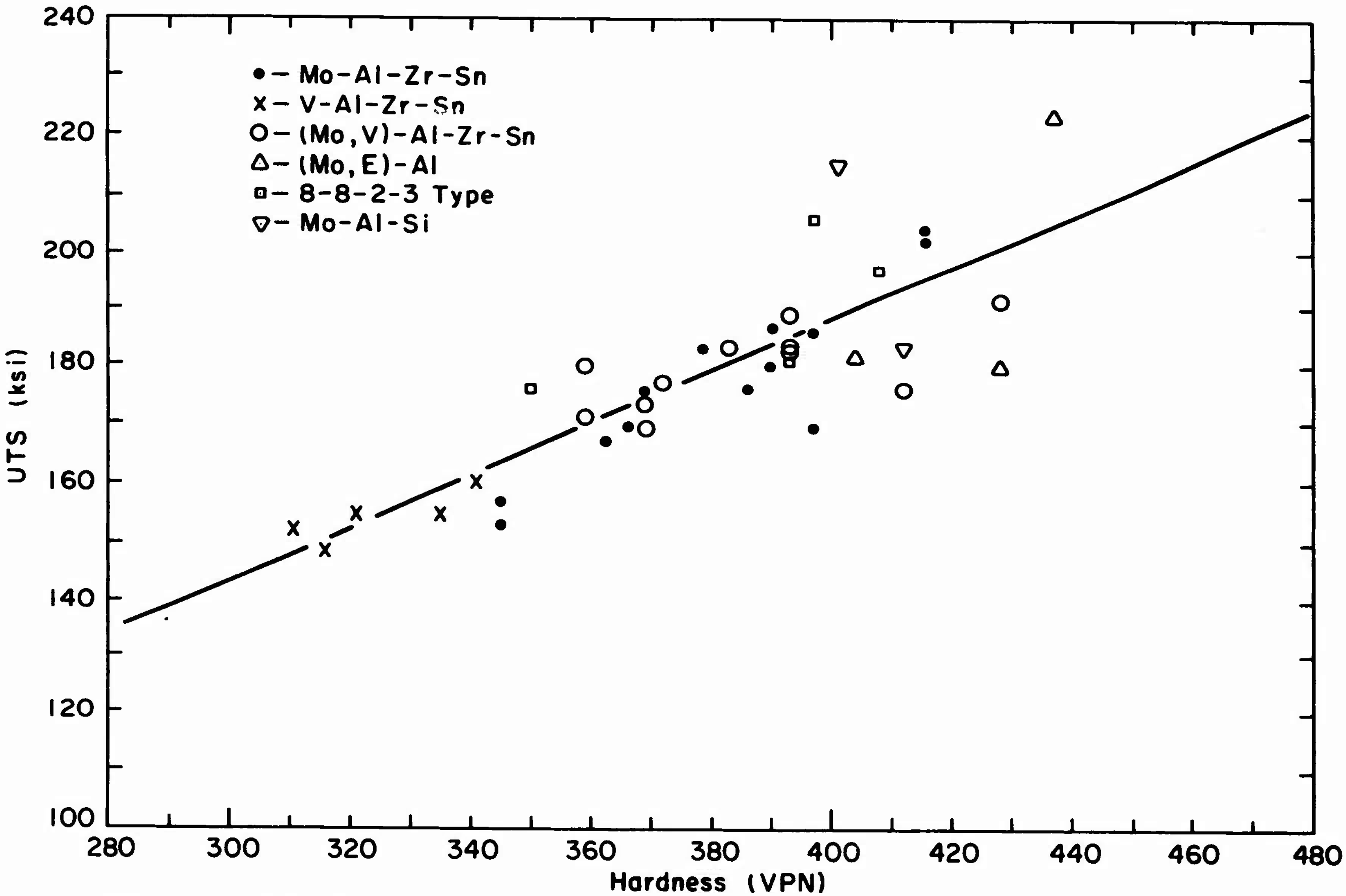


Fig. 1 - Relationship between hardness (VPN) and ultimate tensile strength (UTS) for the Phase I contract alloys. Best fit straight line was obtained by linear regression analysis.

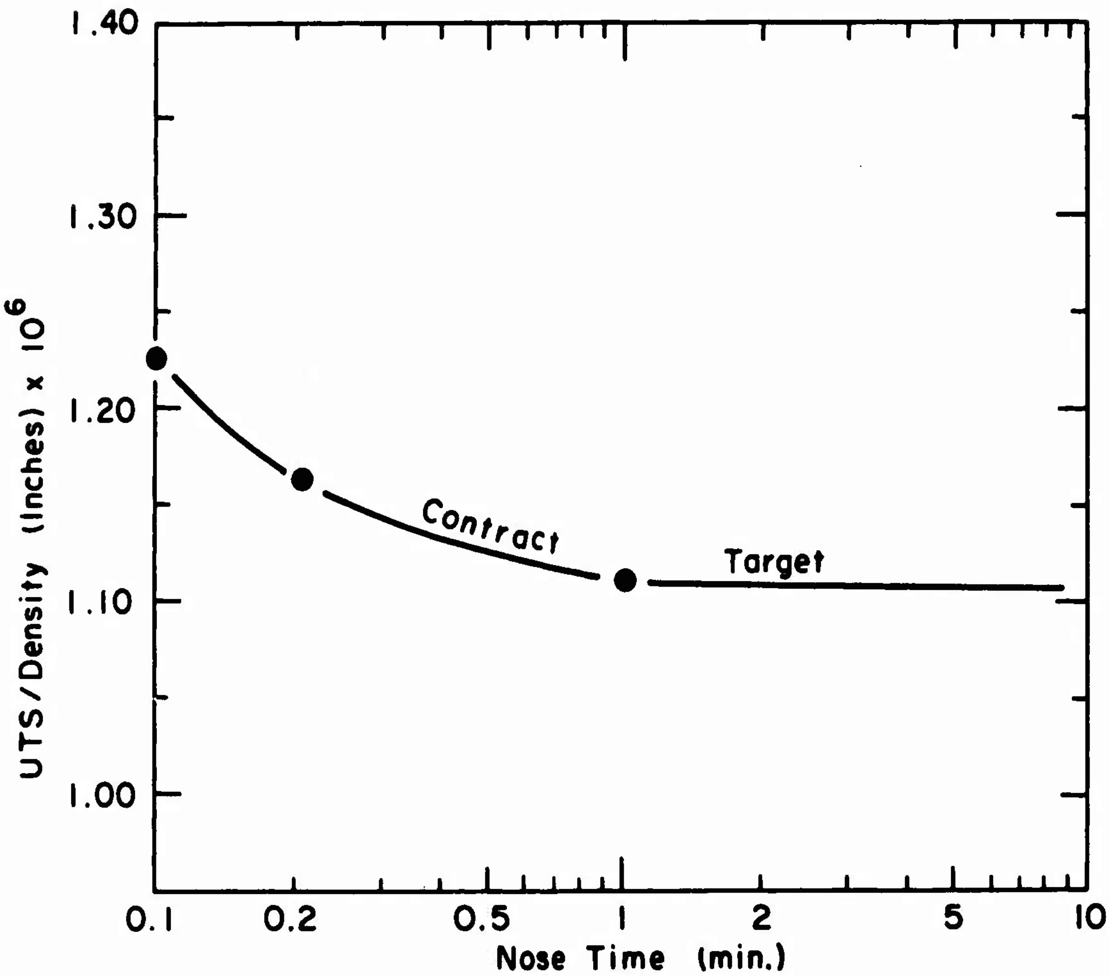


Fig. 2 - Necessary characteristics to meet contract strength goals derived from Table XII, and assuming a required hardness of 400 VPN and a density of 0.169 lbs. ins^{-3}.

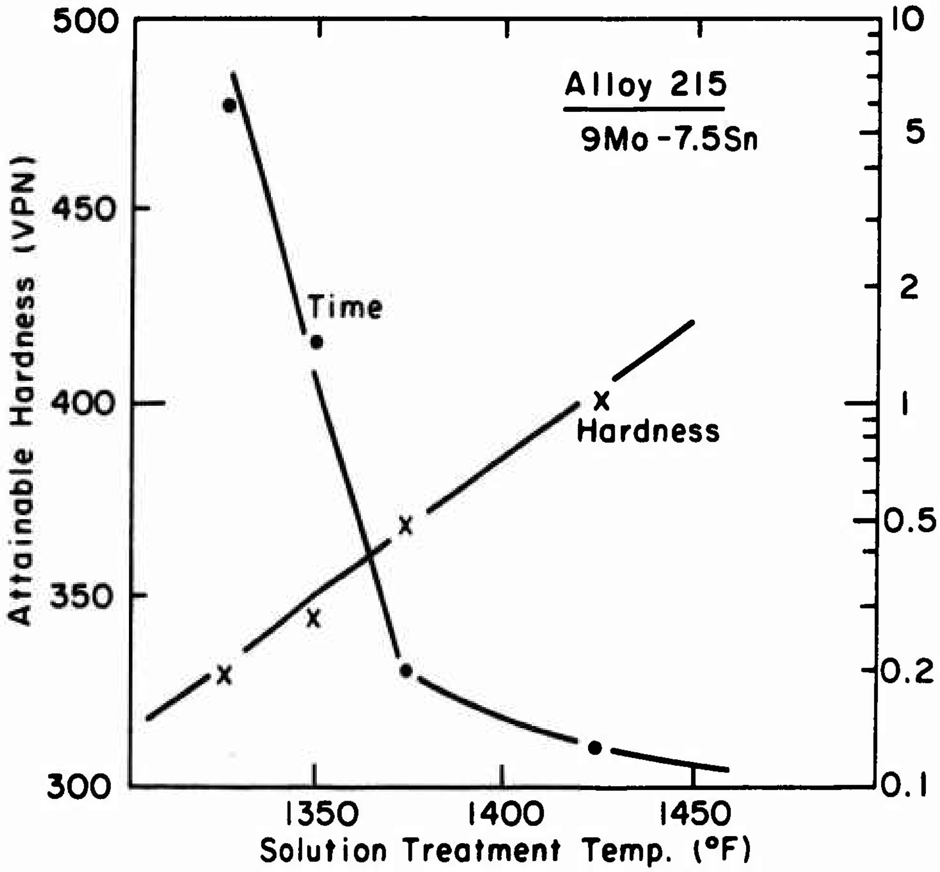


Fig. 3 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 215 - 9Mo-7.5Sn.

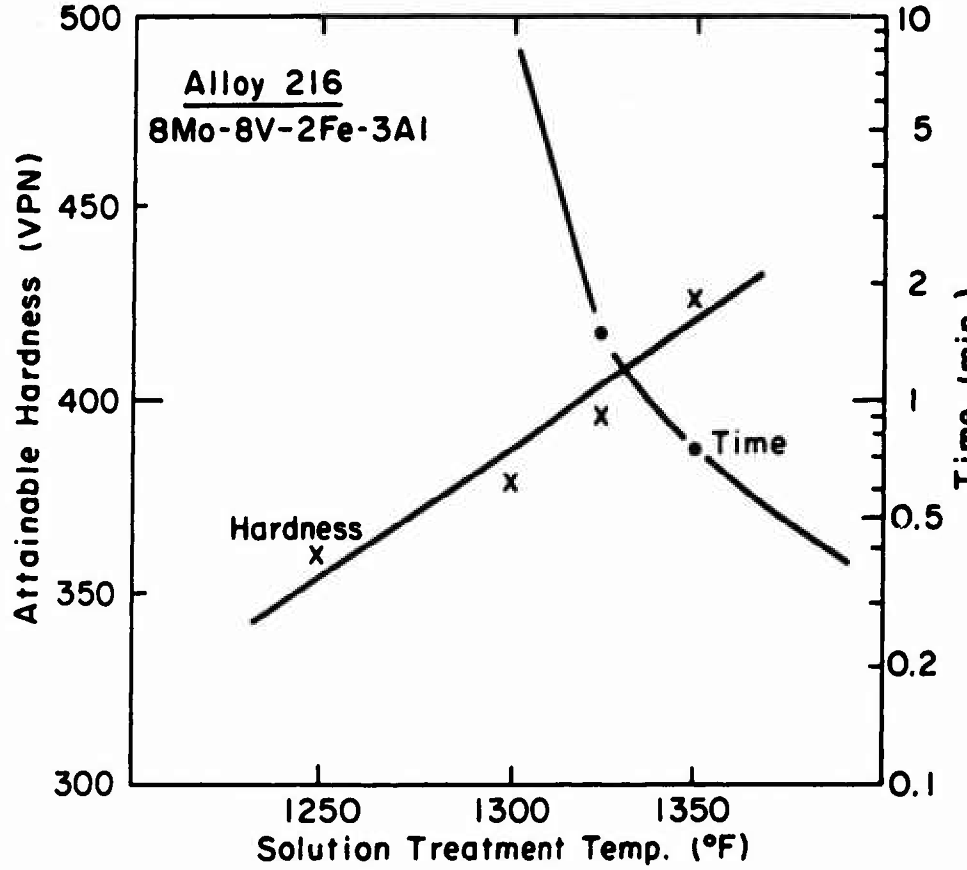


Fig. 4 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 216 - 8Mo-8V-2Fe-3Al.

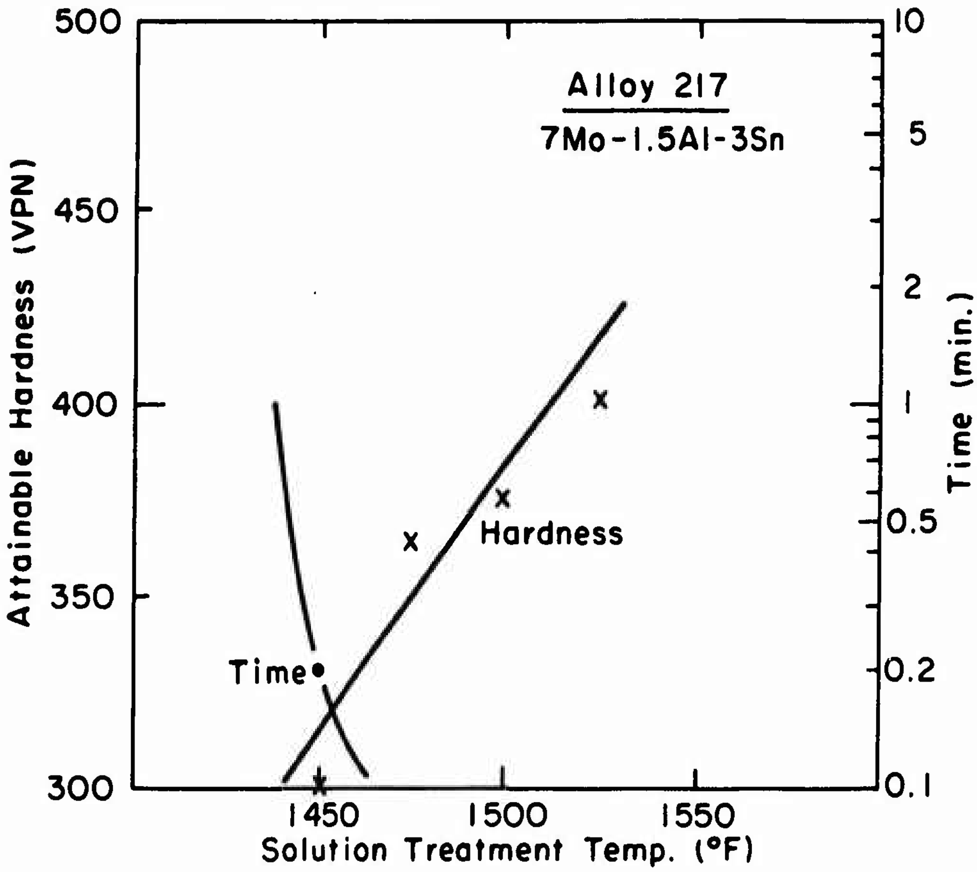


Fig. 5 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 217 - 7Mo-1.5Al-3Sn.

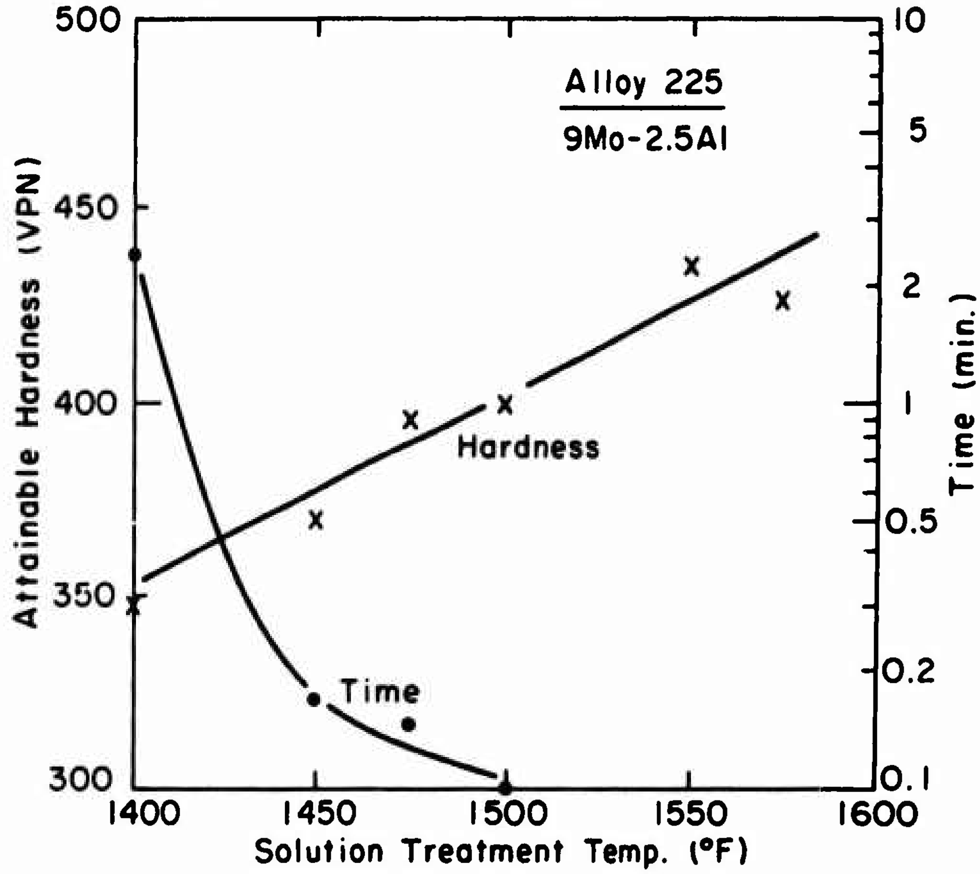


Fig. 6 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 225 - 9Mo-2.5Al.

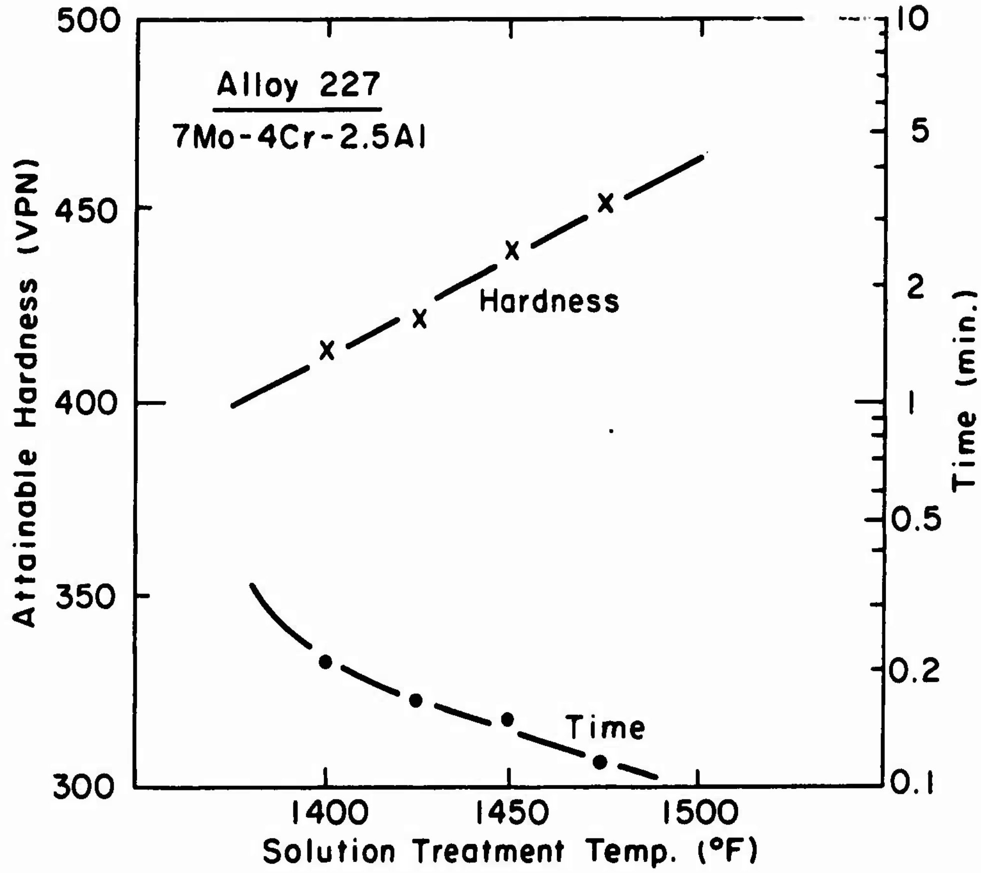


Fig. 7 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 227 - 7Mo-4Cr-2.5Al.

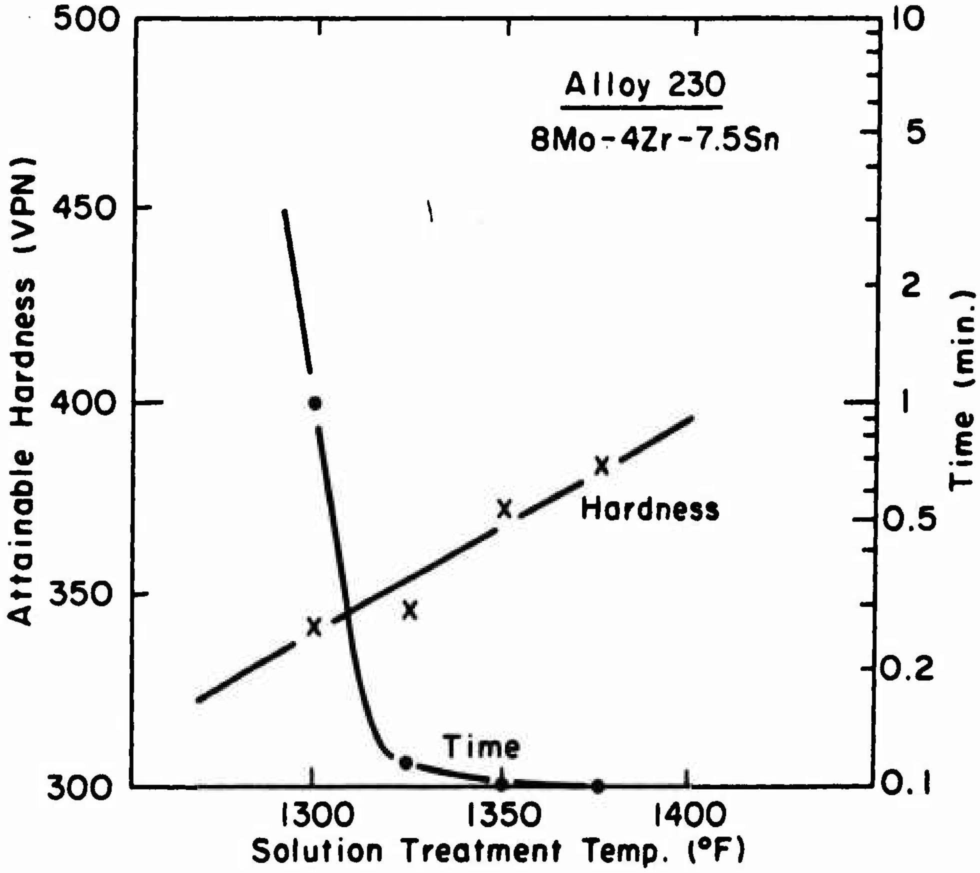


Fig. 8 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 230 - 8Mo-4Zr-7.5Sn.

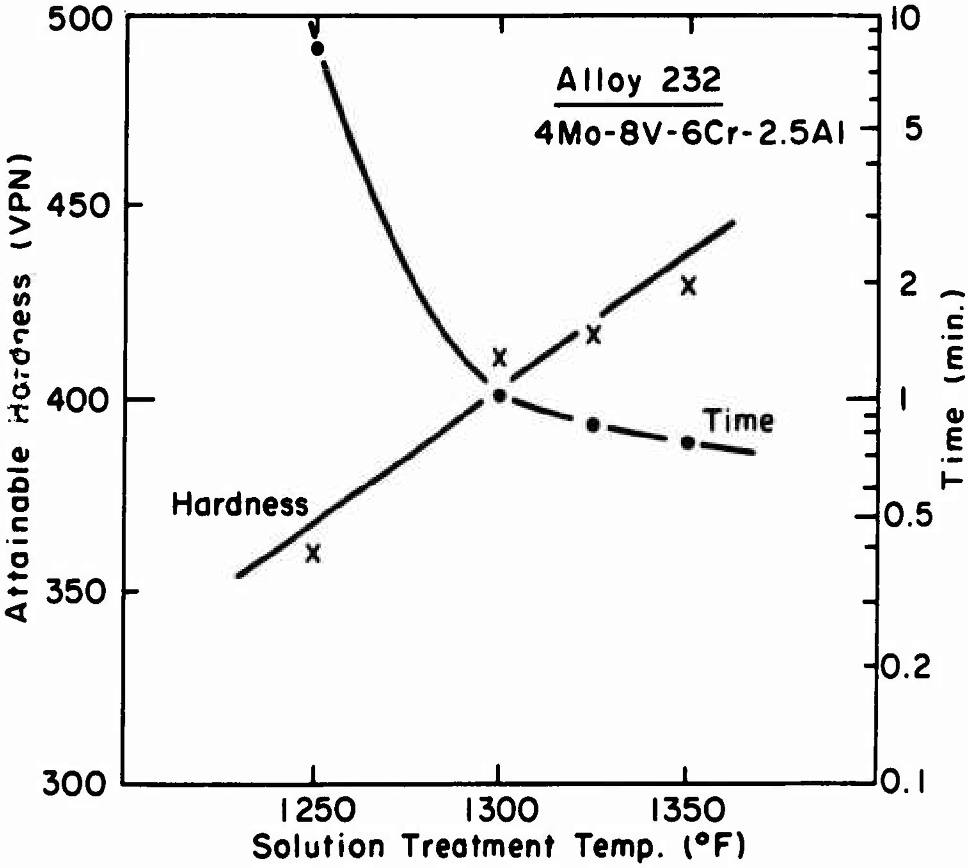


Fig. 9 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 232 - 4Mo-8V-6Cr-2.5Al.

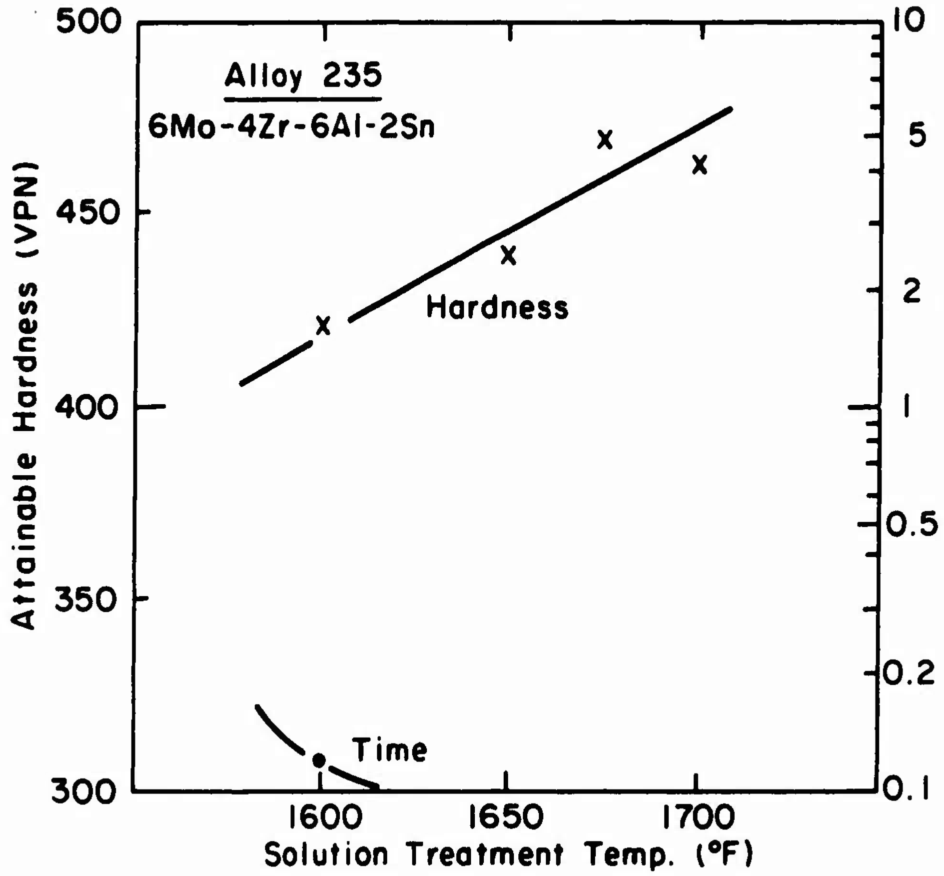


Fig. 10 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 235 - 6Mo-4Zr-6Al-2Sn.

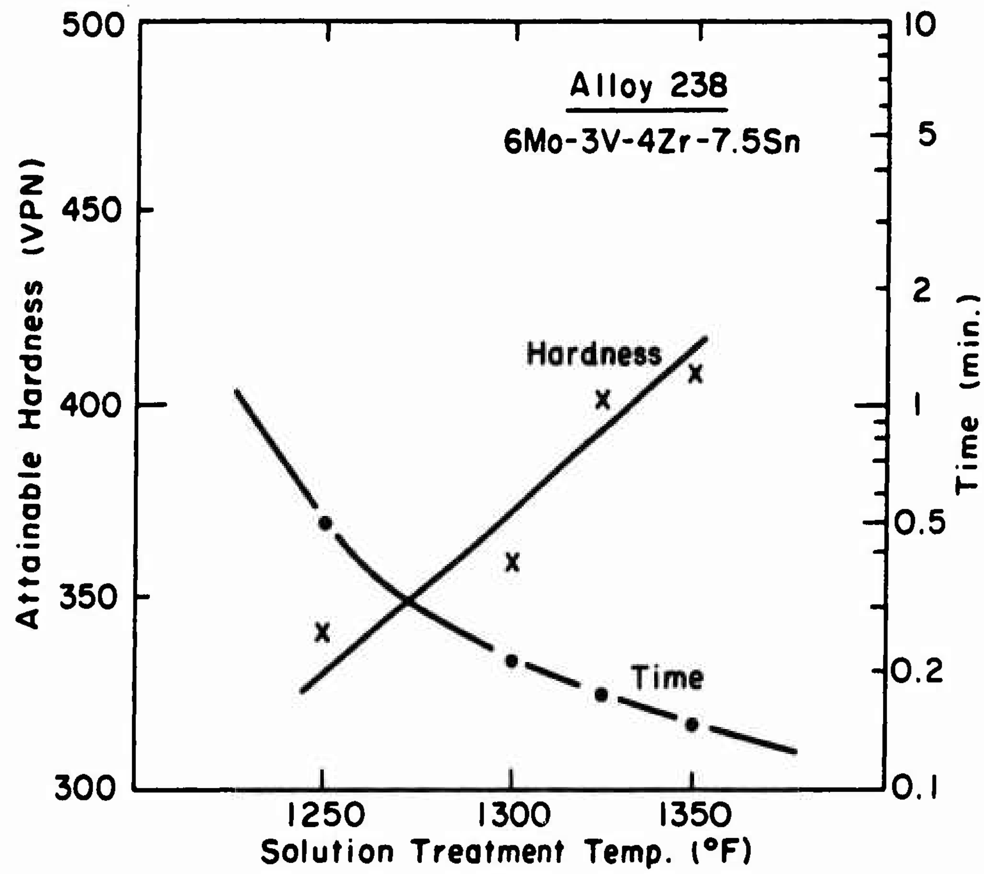


Fig. 11 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 238 - 6Mo-3V-4Zr-7.5Sn.

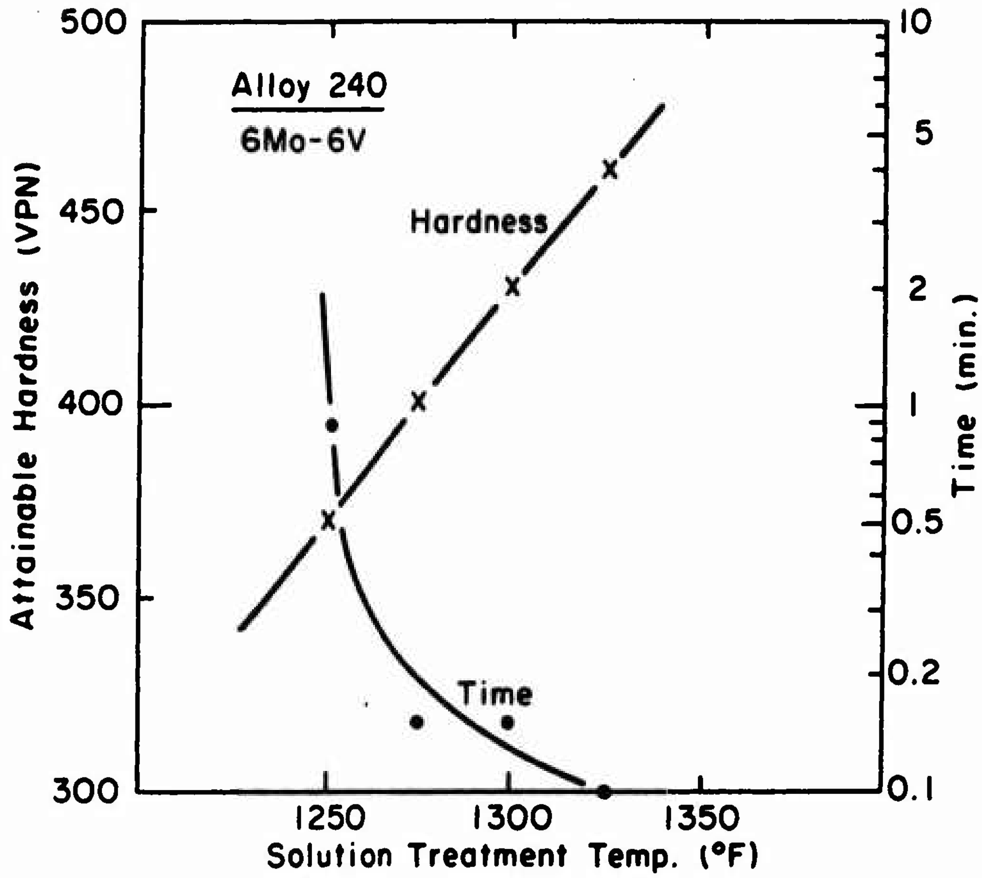


Fig. 12 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 240 - 6Mo-6V.

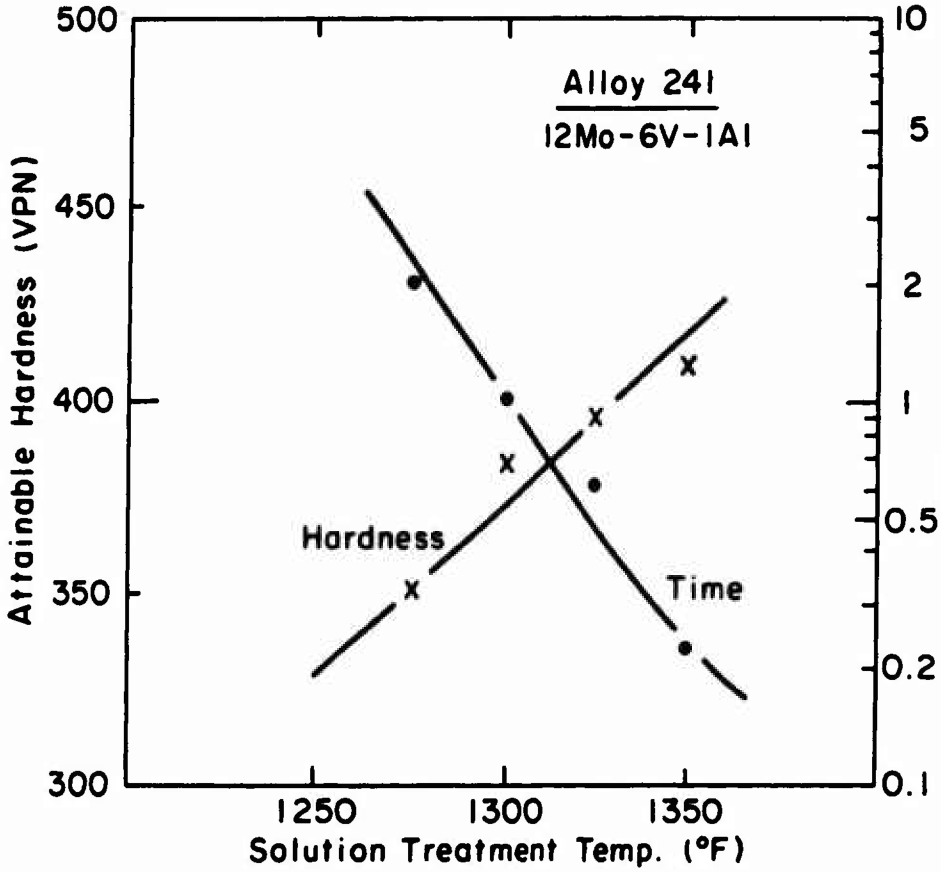


Fig. 13 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 241 - 12Mo-6V-1Al.

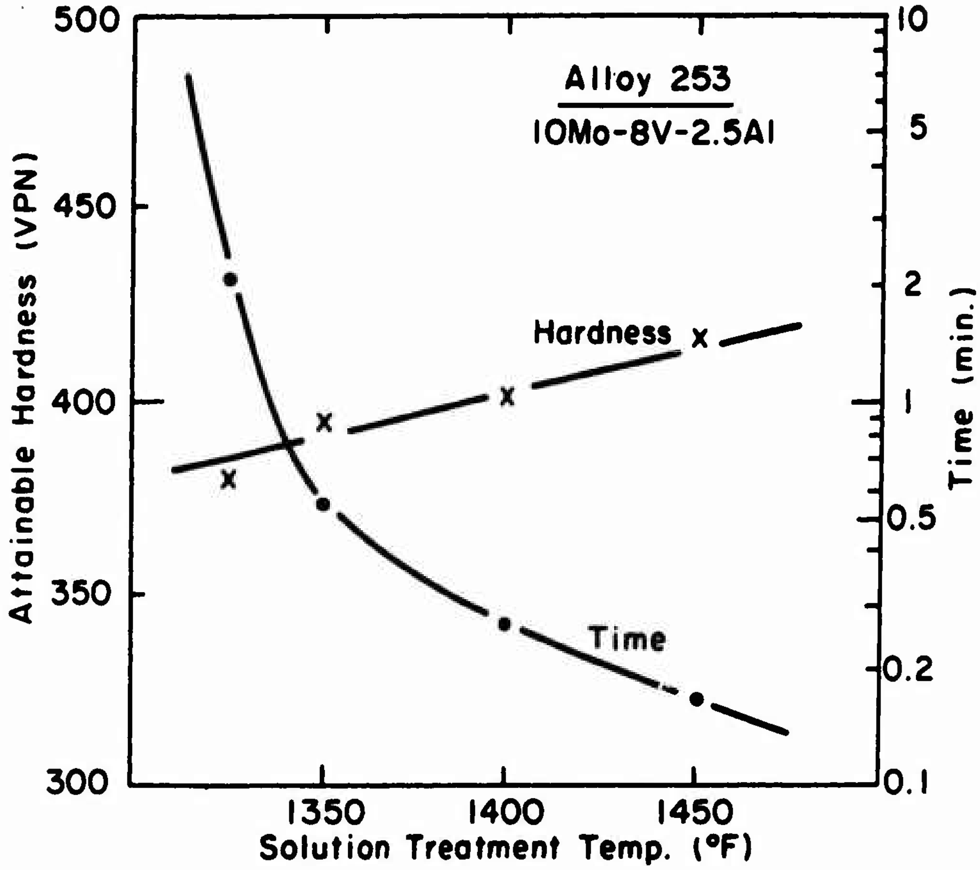


Fig. 14 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 253 - 10Mo-8V-2.5Al.

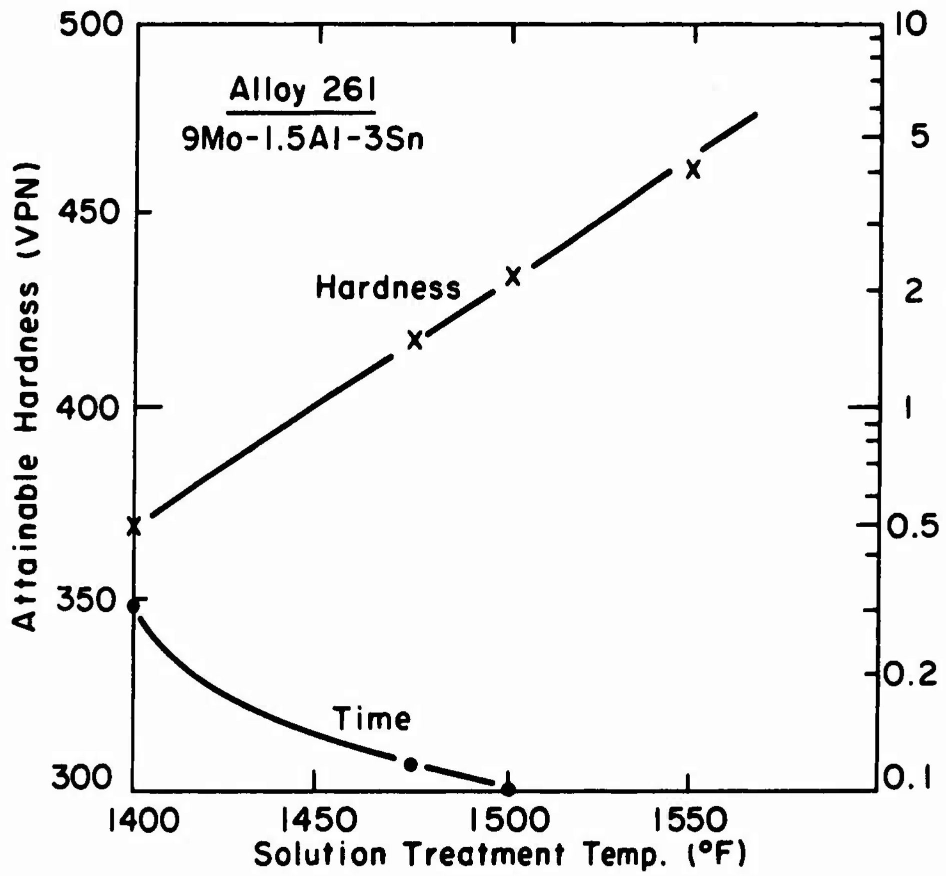


Fig. 15 - Variation of attainable hardness and T-T-T nose time with solution treatment temperature. Alloy 261 - 9Mo-1.5Al-3Sn.

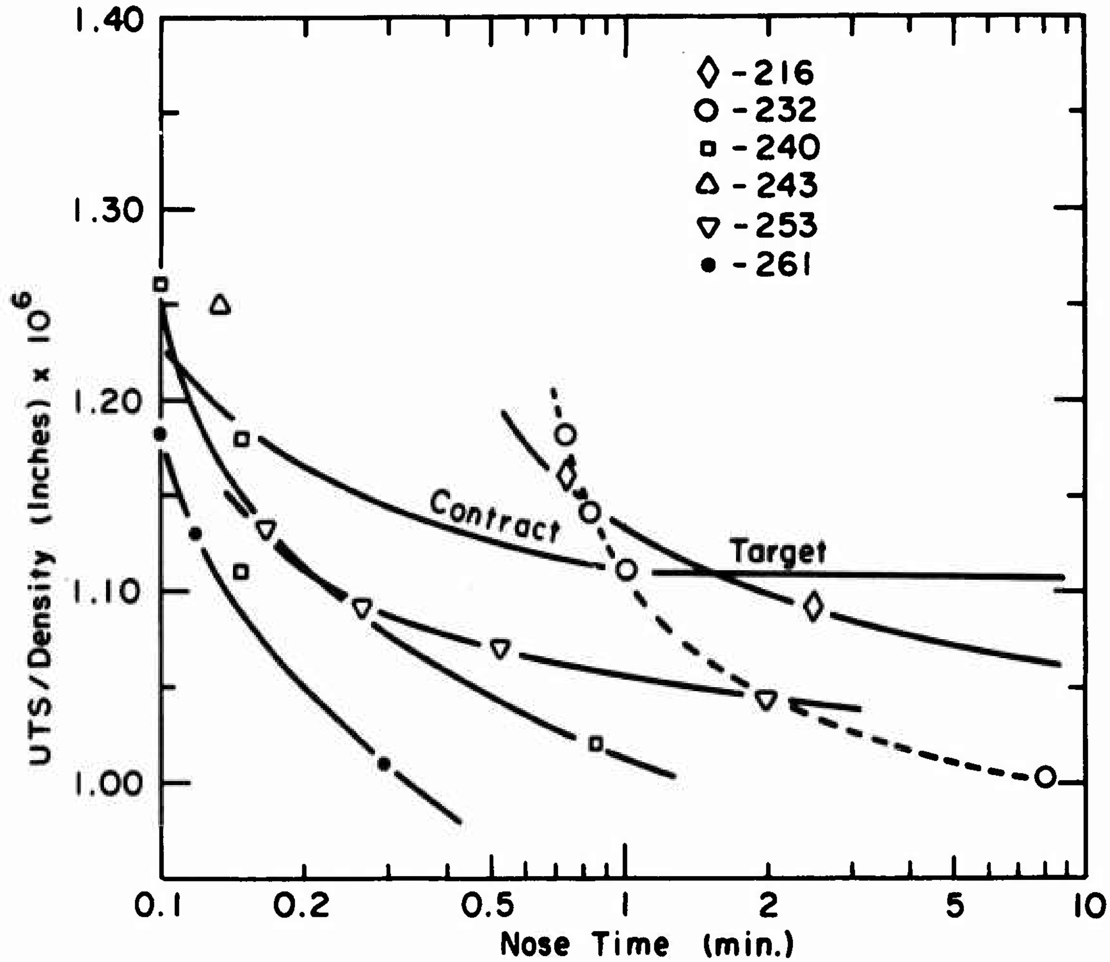


Fig. 16 - Comparison of strength potential and nose time of selected "good" alloys with contract target curve. Alloy parameters are obtained directly from Figures 3-15, hardness values being converted to UTS (Figure 1) and normalized by dividing by density.
Alloy 216 - 8Mo-8V-2Fe-3Al
Alloy 232 - 4Mo-8V-6Cr-2.5Al
Alloy 240 - 6Mo-6V
Alloy 243 - 11Mo-1Al-0.5Si
Alloy 253 - 10Mo-8V-2.5Al
Alloy 261 - 9Mo-1.5Al-3Sn

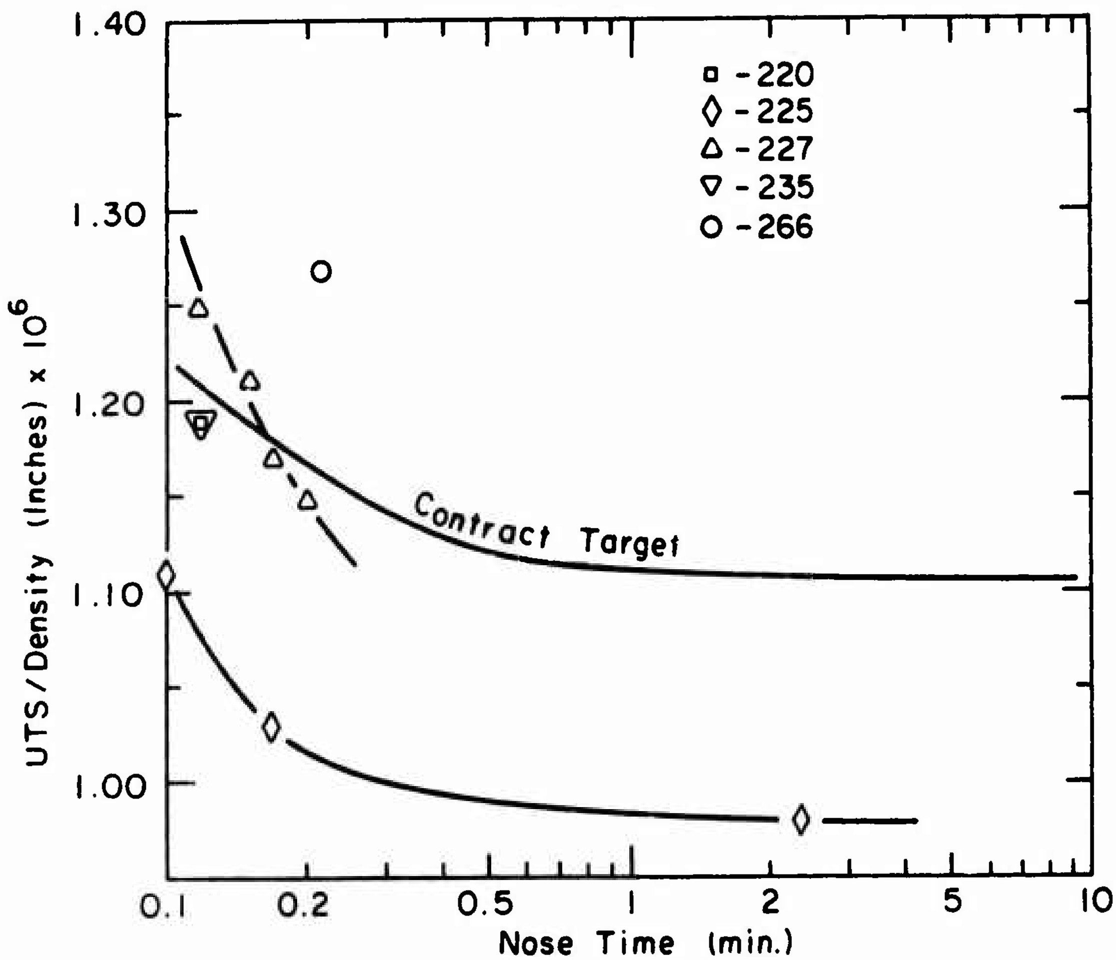


Fig. 17- Comparison of strength potential and nose time of selected "good" alloys with contract target curve. Alloy parameters are obtained directly from Figures 3-15, hardness values being converted to UTS (Figure 1) and normalized by dividing by density.

Alloy 220 - 11Mo-2.5Al
Alloy 225 - 9Mo-2.5Al
Alloy 227 - 7Mo-4Cr-2.5Al
Alloy 232 - 4Mo-8V-6Cr-2.5Al
Alloy 266 - 11Mo-4Al

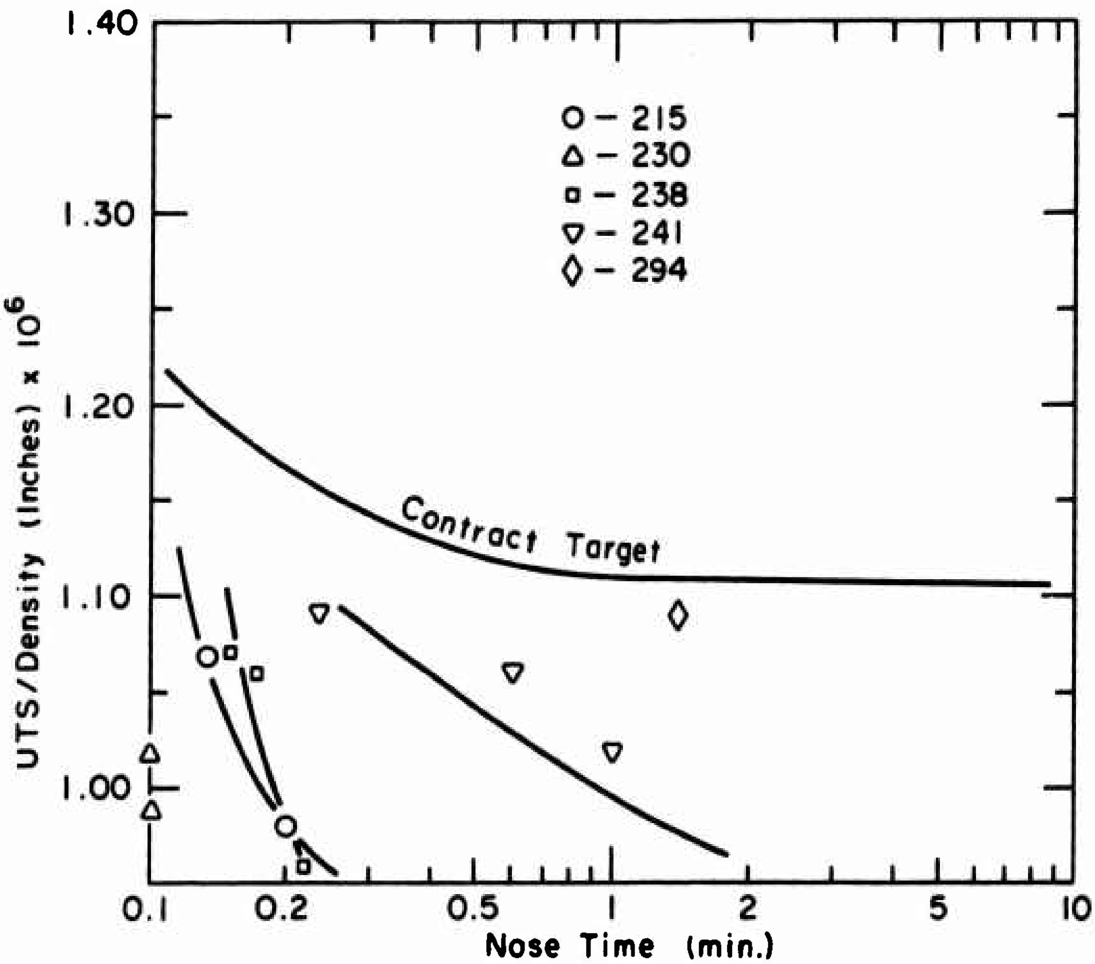


Fig. 18 - Comparison of strength potential and nose time of selected "good" alloys with contract target curve. Alloy parameters are obtained directly from Figures 3-15, hardness values being converted to UTS (Figure 1) and normalized by dividing by density.
Alloy 215 - 9Mo-7.5Sn
Alloy 230 - 8Mo-4Zr-7.5Sn
Alloy 238 - 6Mo-3V-4Zr-7.5Sn
Alloy 241 - 12Mo-6V-1Al
Alloy 294 - 11.5Mo-6Zr-4.5Sn

Fig. 19 - Alloy 261, ST 1450F-2 hrs, aged 900F-4 hrs.

Fig. 20 - Alloy 227, ST 1400F-4 hrs, aged 900F-8 hrs.

Transverse cross section of simulated cooled Charpy. X8.5

Fig. 21 - Alloy 216, ST 1300F-4 hrs, aged 900F-96 hrs.

Fig. 22 - Alloy 334, ST 1325F-4 hrs, aged 875F-96 hrs.

Transverse cross section of simulated cooled Charpy. X8.5

Fig. 23 - Alloy 337, ST 1350F-4 hrs, aged 875F-24 hrs.

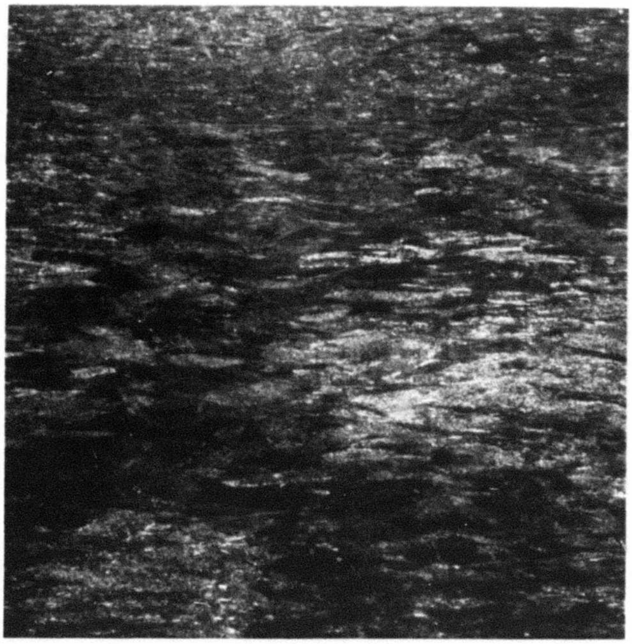


Fig. 24 - Alloy 235, ST 1575F-1 hr, aged 1100F-8 hrs.

Transverse cross section of simulated cooled Charpy. X8.5

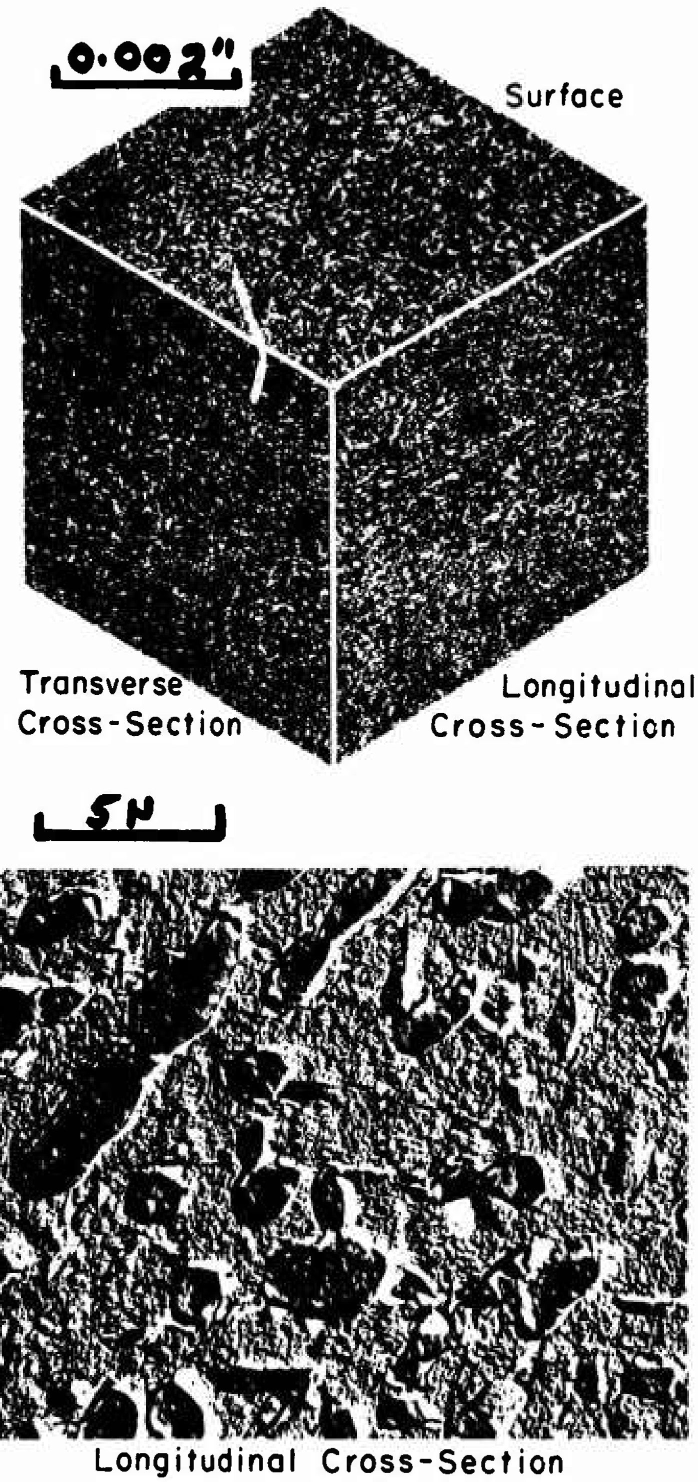
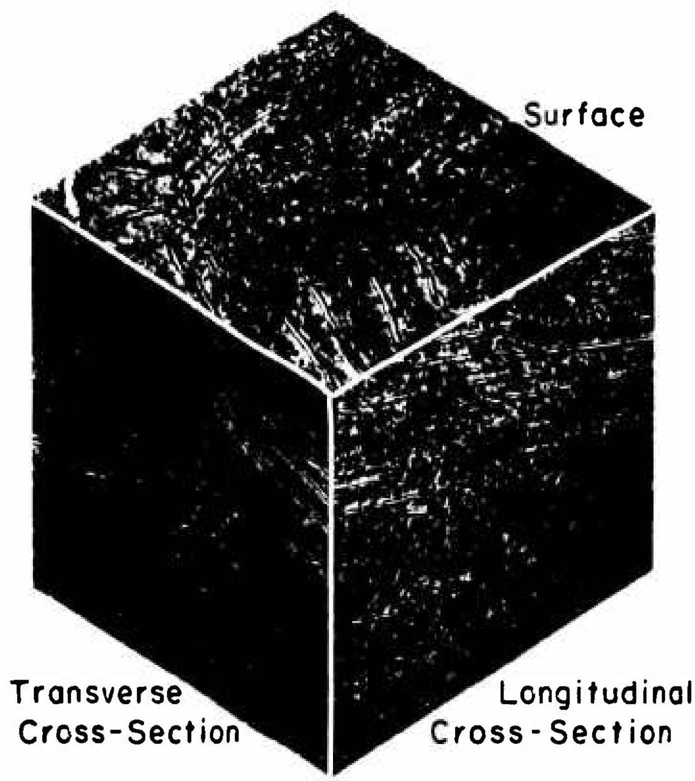
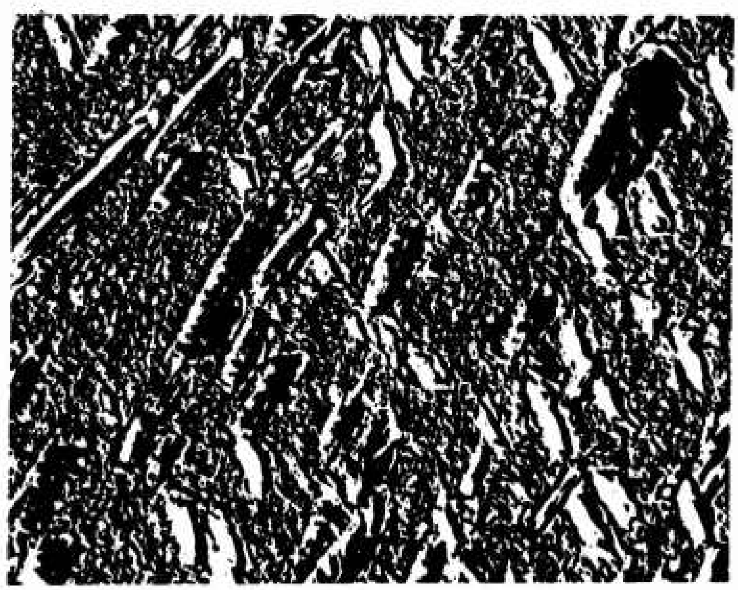


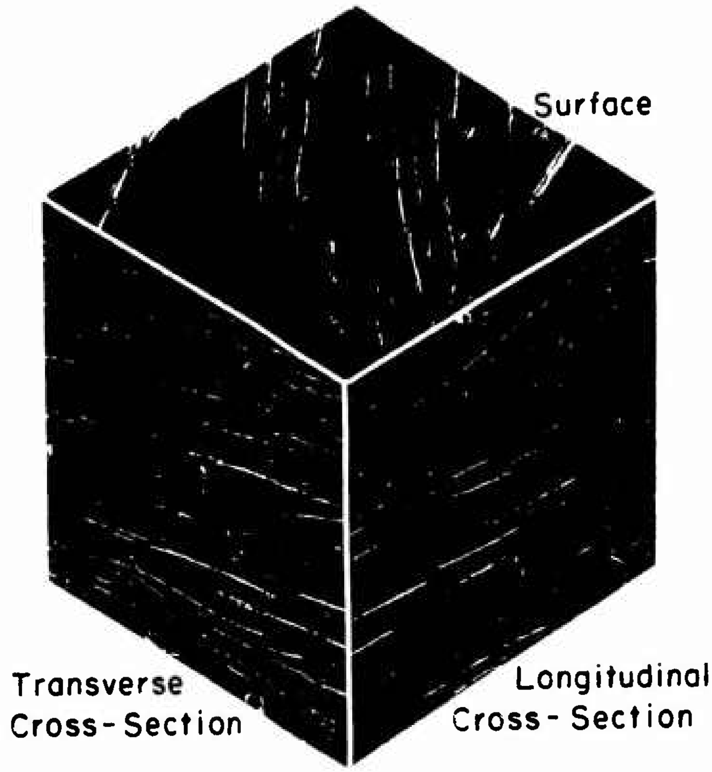
Fig. 25 - Alloy 261, ST 1450F-2 hrs, simulated cooled, aged 900F - 4 hrs. Optical isometric X500. Surface replica X5,200.

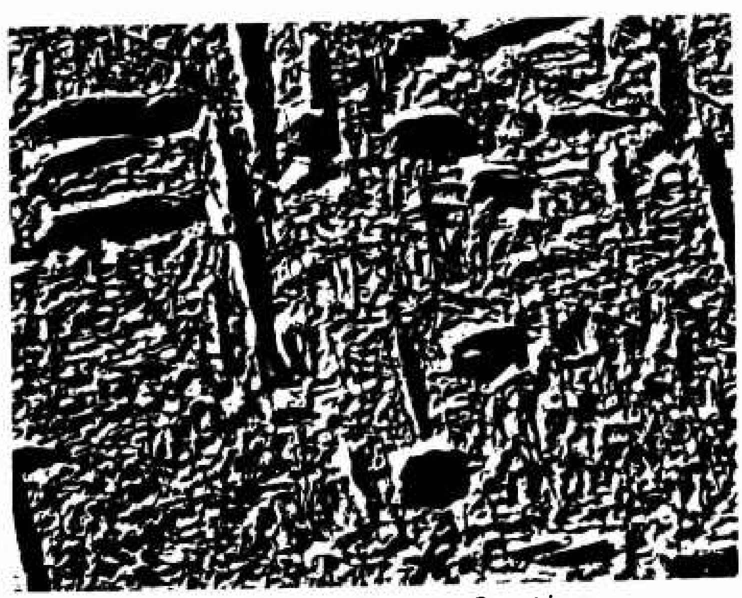




Longitudinal Cross-Section

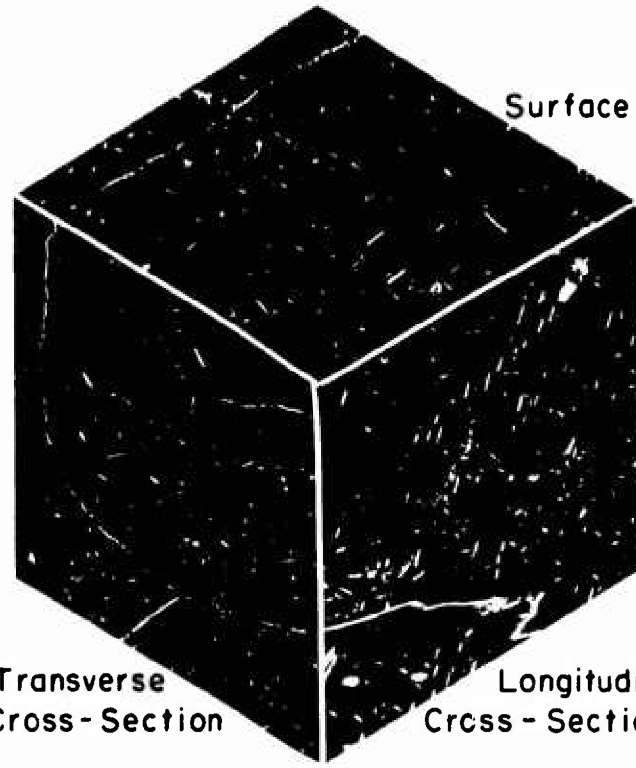
Fig. 26 - Alloy 227, ST 1400F-4 hrs, simulated cooled, aged 900F-hrs. Optical isometric X500. Surface replica X5,200.

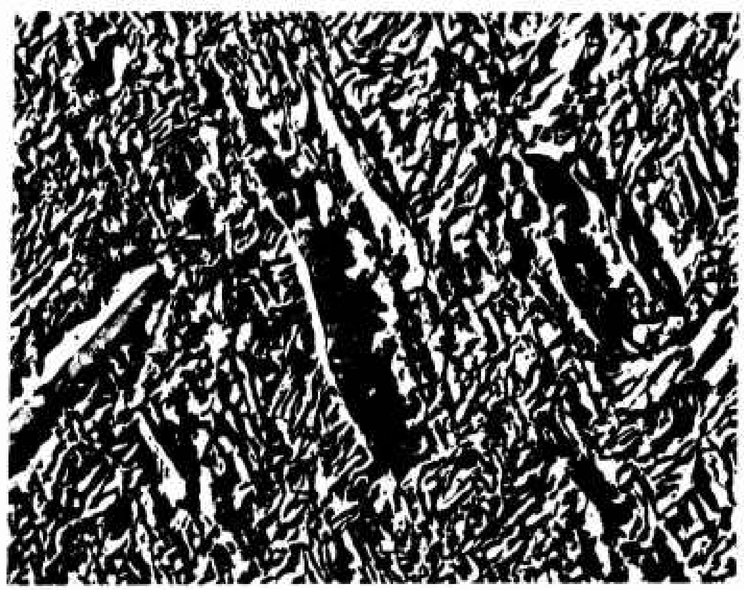




Longitudinal Cross-Section

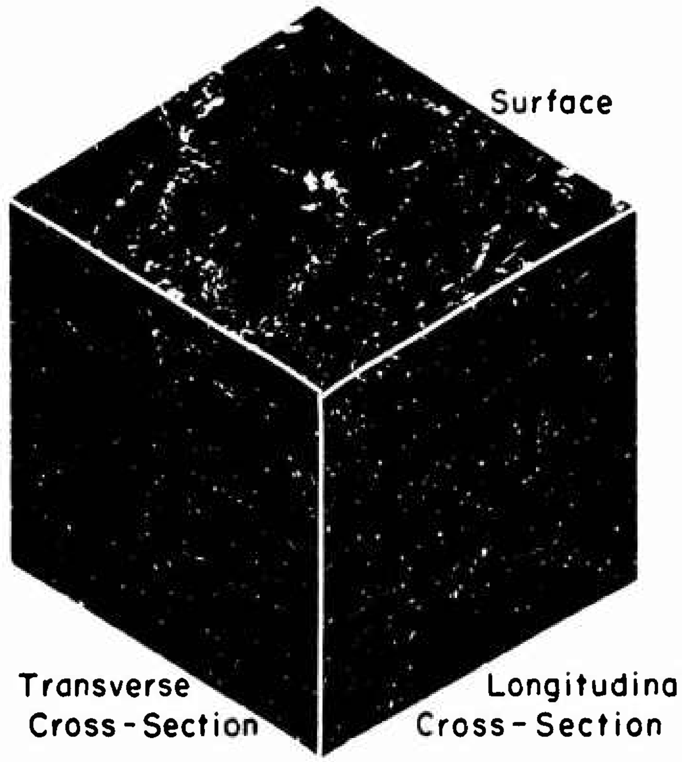
Fig. 27 - Alloy 216, ST 1300F-4 hrs, simulated cooled, aged 900F-96 hrs. Optical isometric X500. Surface replica X5,200.

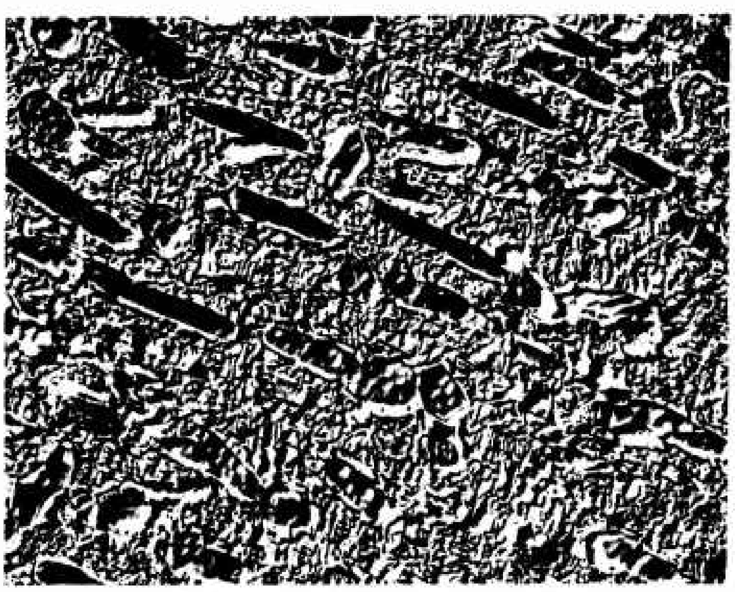




Longitudinal Cross-Section

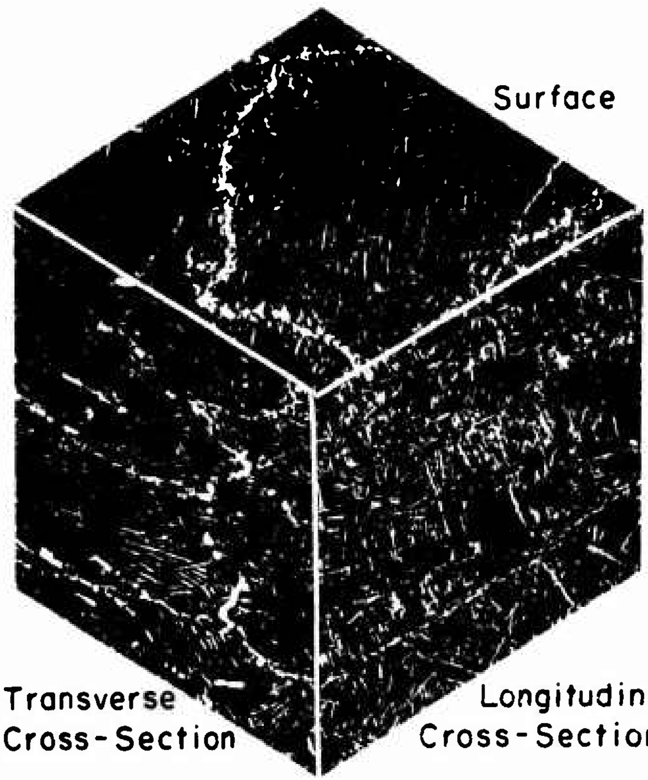
Fig. 28 - Alloy 334, ST 1325F-4 hrs, simulated cooled, aged 875F-96 hrs. Optical isometric X500. Surface replica X5,200.





Longitudinal Cross-Section

Fig. 29 - Alloy 337, ST 1350F-4 hrs, simulated cooled, aged 875F-24 hrs. Optical isometric X500. Surface replica X5,200.



Longitudinal Cross-Section

Fig. 30 - Alloy 235, ST 1575F-1 hr, simulated cooled, aged 1100F-8 hrs. Optical isometric X500. Surface replica X5,200.

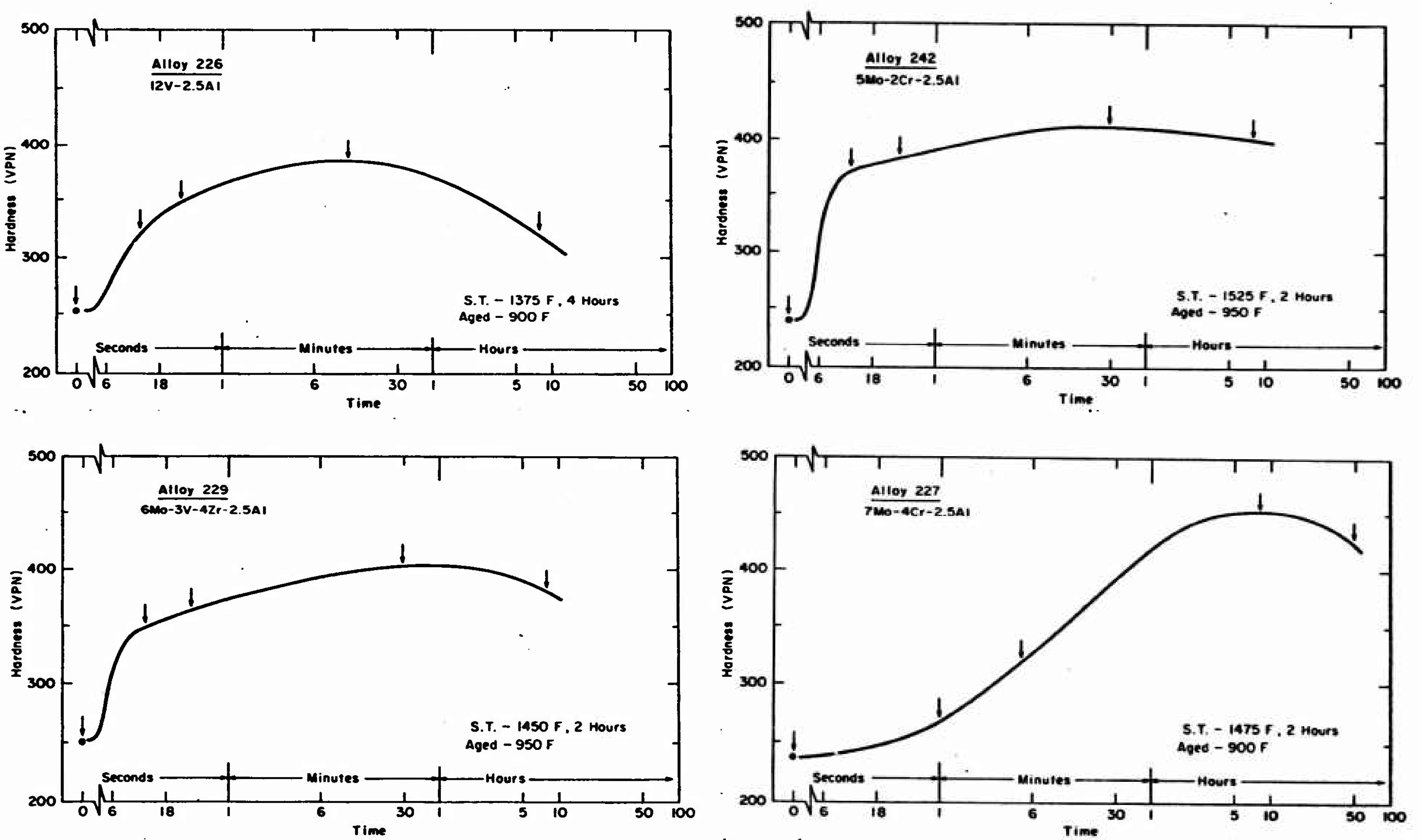
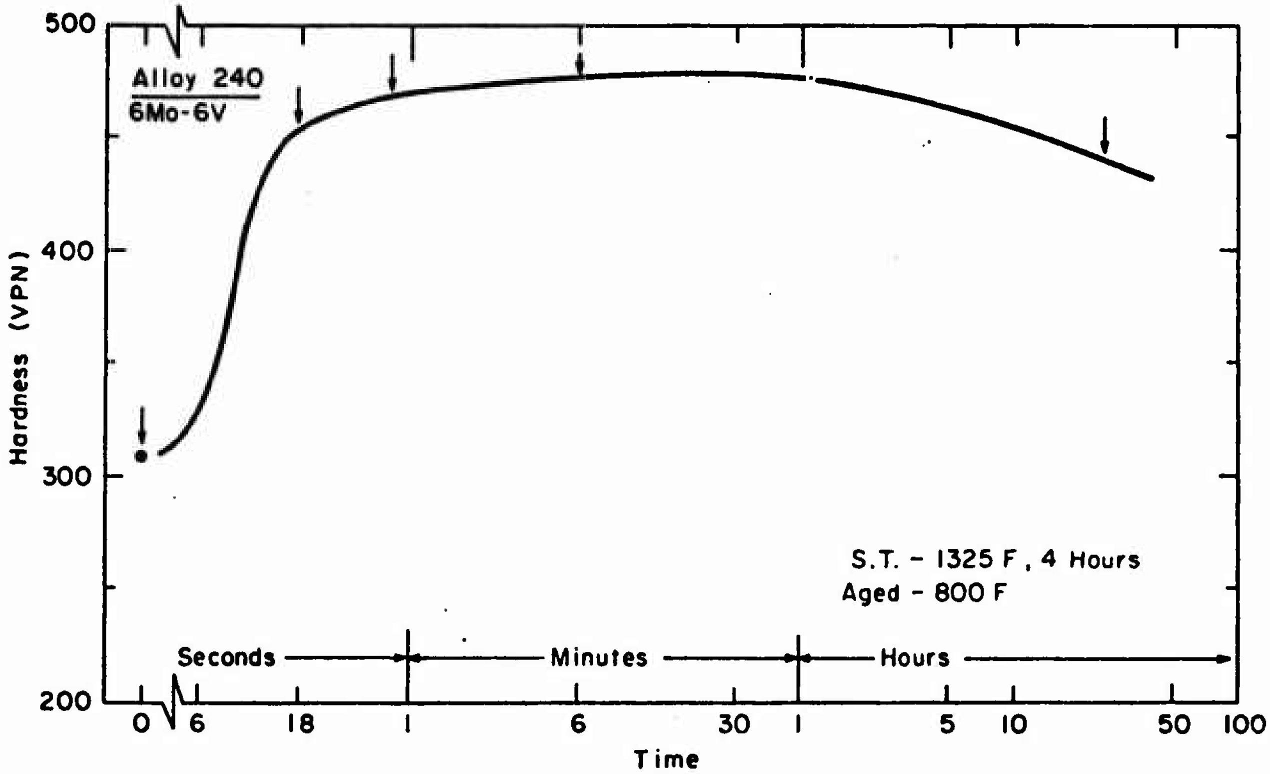


Figure 31 - Hardening response for alloys containing primary alpha and orthorhombic martensite as solution treated.

↓: Samples examined for fine structure analysis.



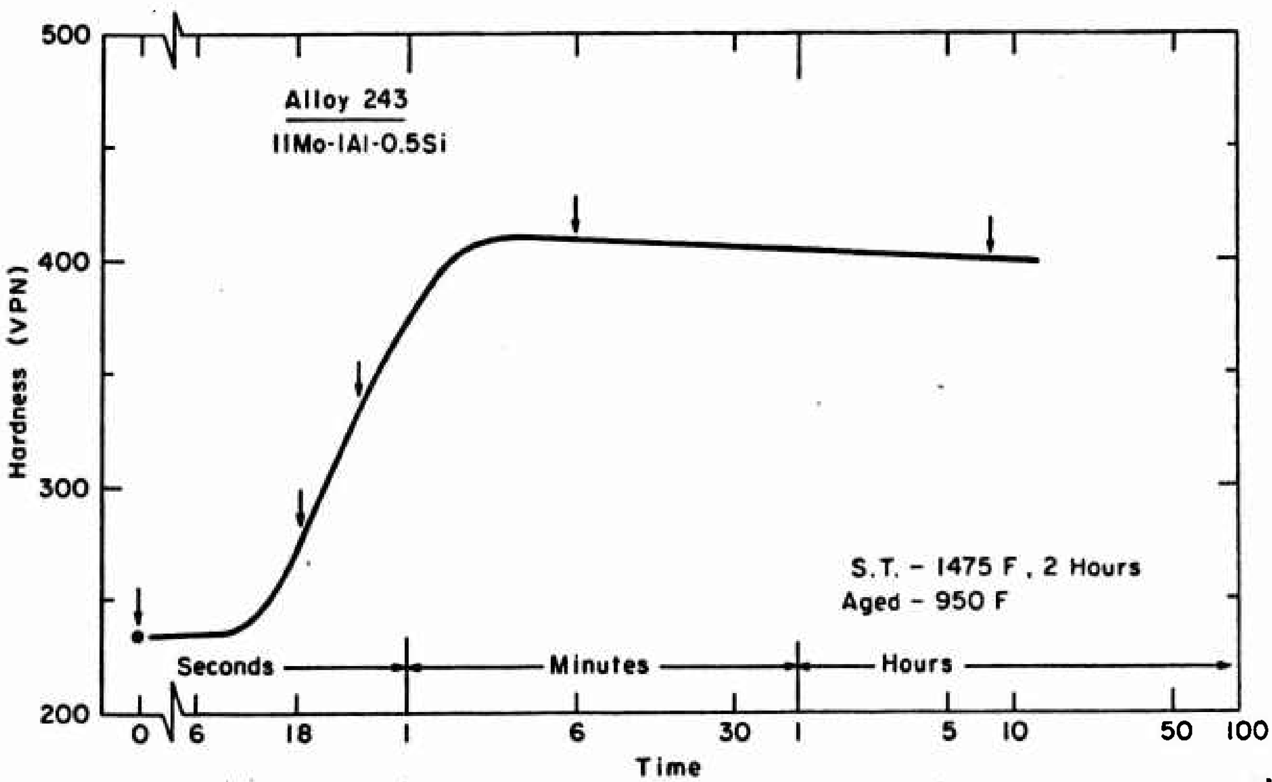


Figure 32 - Hardening response for alloys containing primary alpha, beta and omega.

↓: Samples examined for fine structure analysis.

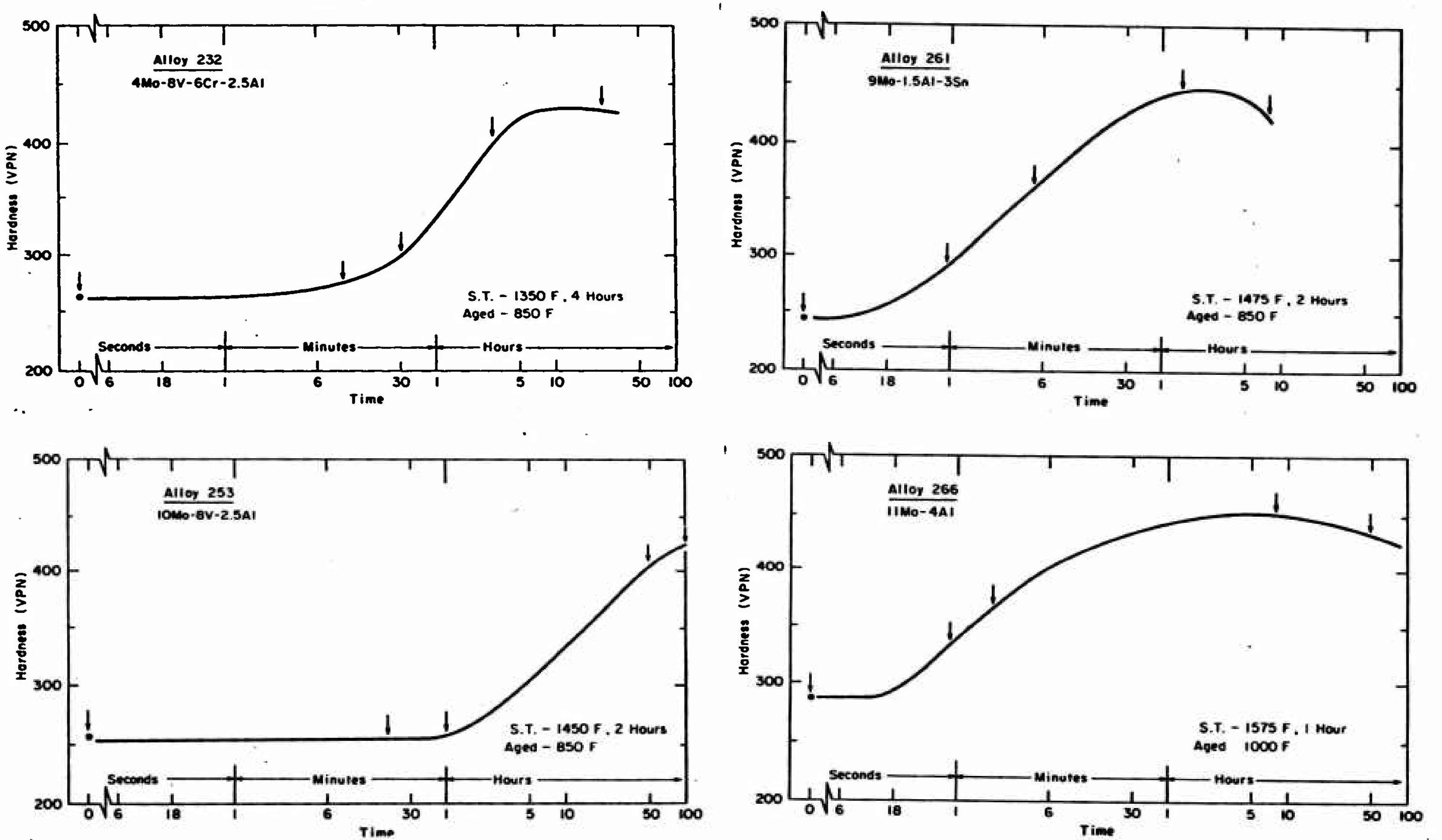
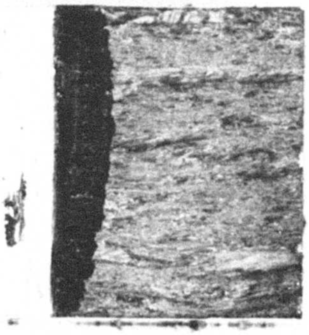
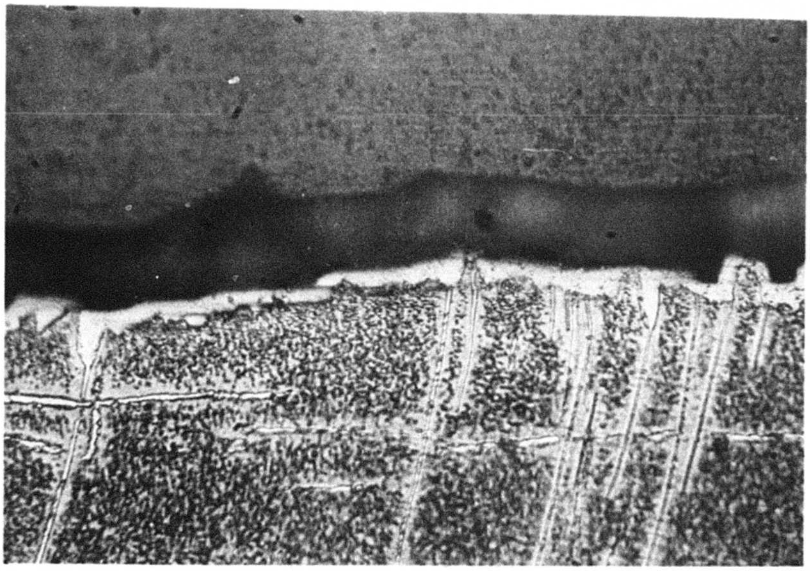


Figure 33 - Hardening response for alloys containing primary alpha and beta.

↓: Samples examined for fine structure analysis.



Fracture surface transverse (WR) Charpy X4



Fracture path from above. Crack propagated right to left. X500

Fig. 34 - Alloy 227, ST 1400F-4 hrs, simulated cooled, aged 900F-8 hrs.

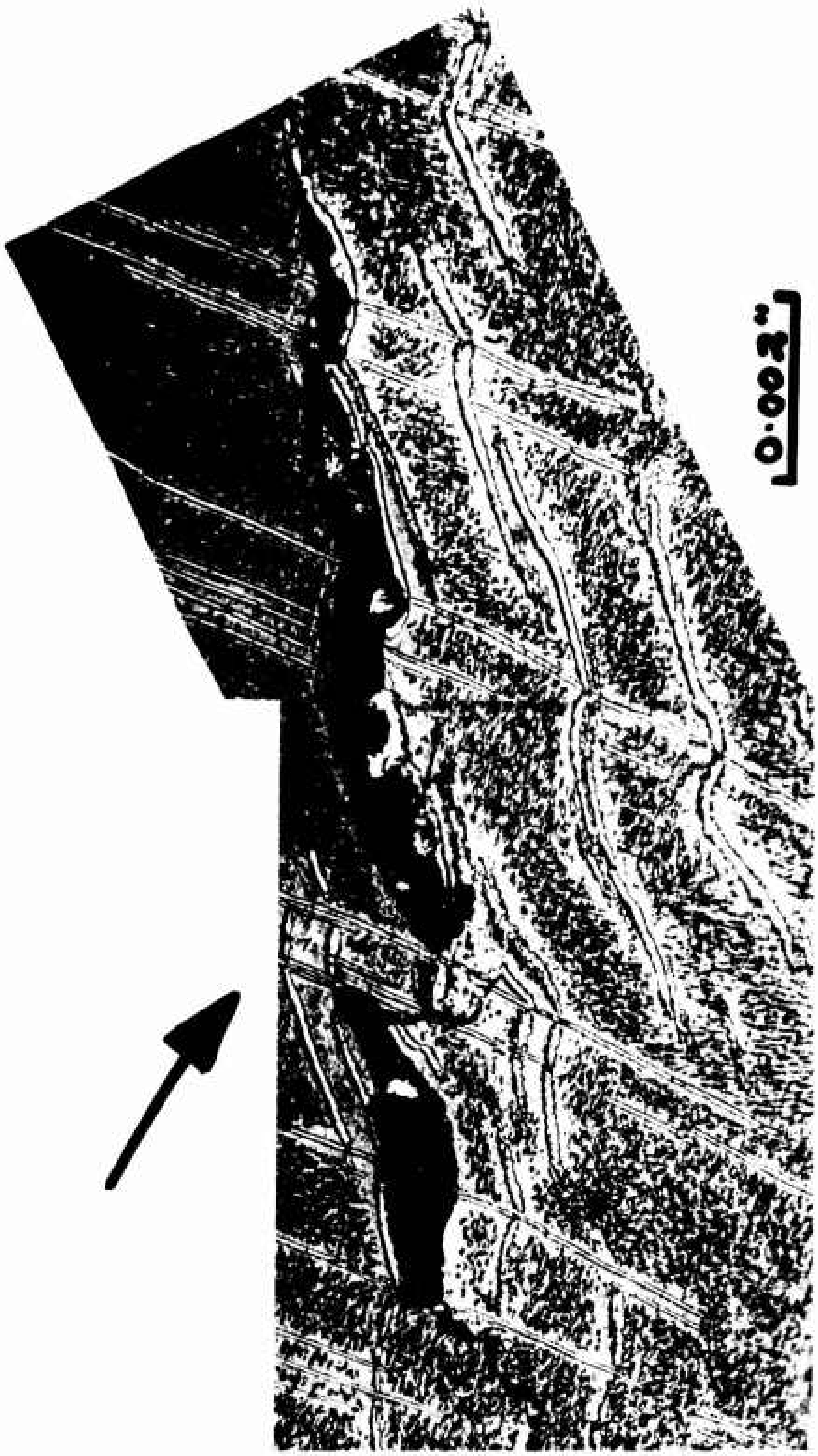
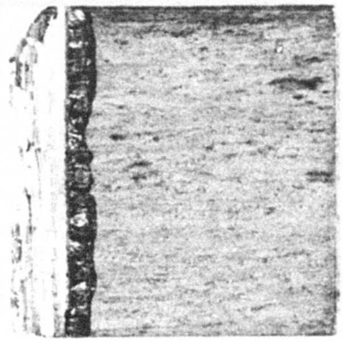
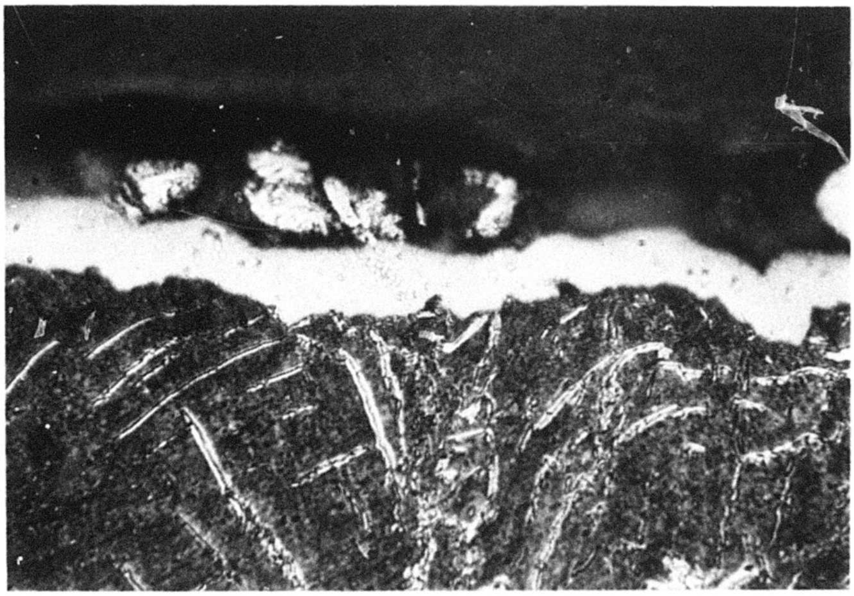


Fig. 35 - Alloy 227, ST 1400-4 hrs, simulated cooled, aged 900F-8 hrs.
Internal fracture path from Fig. 52. Crack propagated bottom to top. X500

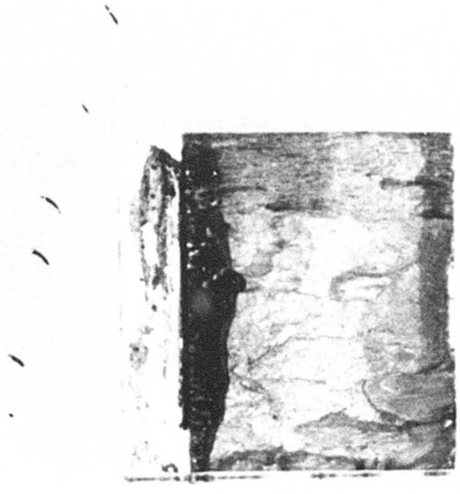


Fracture surface transverse (WR) Charpy X4



Fracture path from above. Crack propagated righ to left. X500

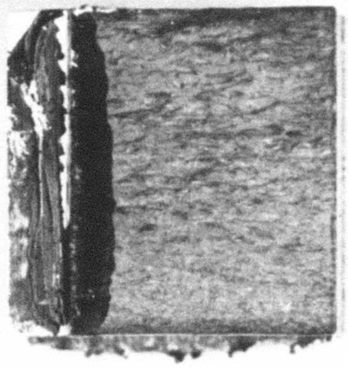
Fig. 36 - Alloy 216, ST 1300F-4 hrs, simulated cooled, aged 900F-96 hrs.



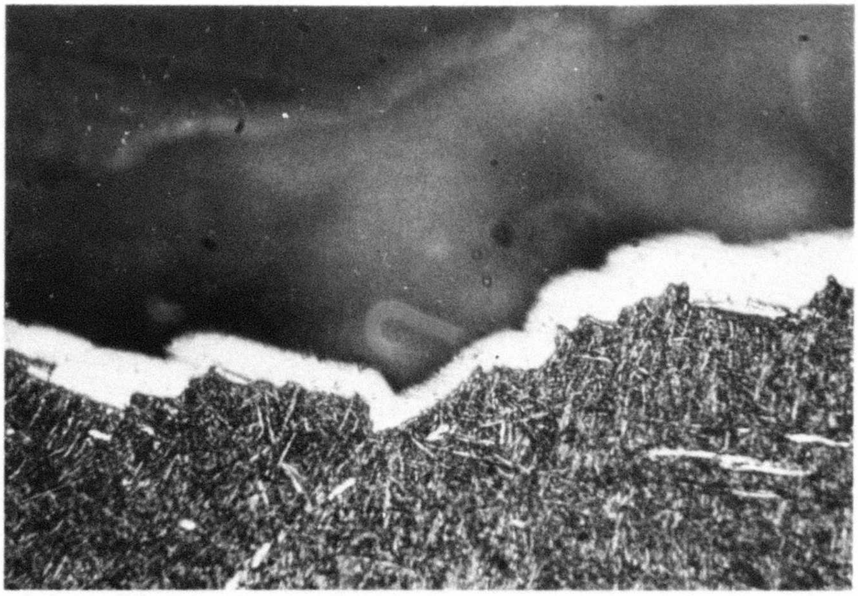
Fracture surface transverse (WR) Charpy X4

Fracture path from above. Crack propagated left to right. X500

Fig. 37 - Alloy 334, ST 1325F-4 hrs, simulated cooled, aged 875F-96 hrs.



Fracture surface transverse (WR) Charpy X4



Fracture path from above. Crack propagated left to right. X500

Fig. 38 - Alloy 235, ST 1575F-1 hr, simulated cooled, aged 1100F-8 hrs.

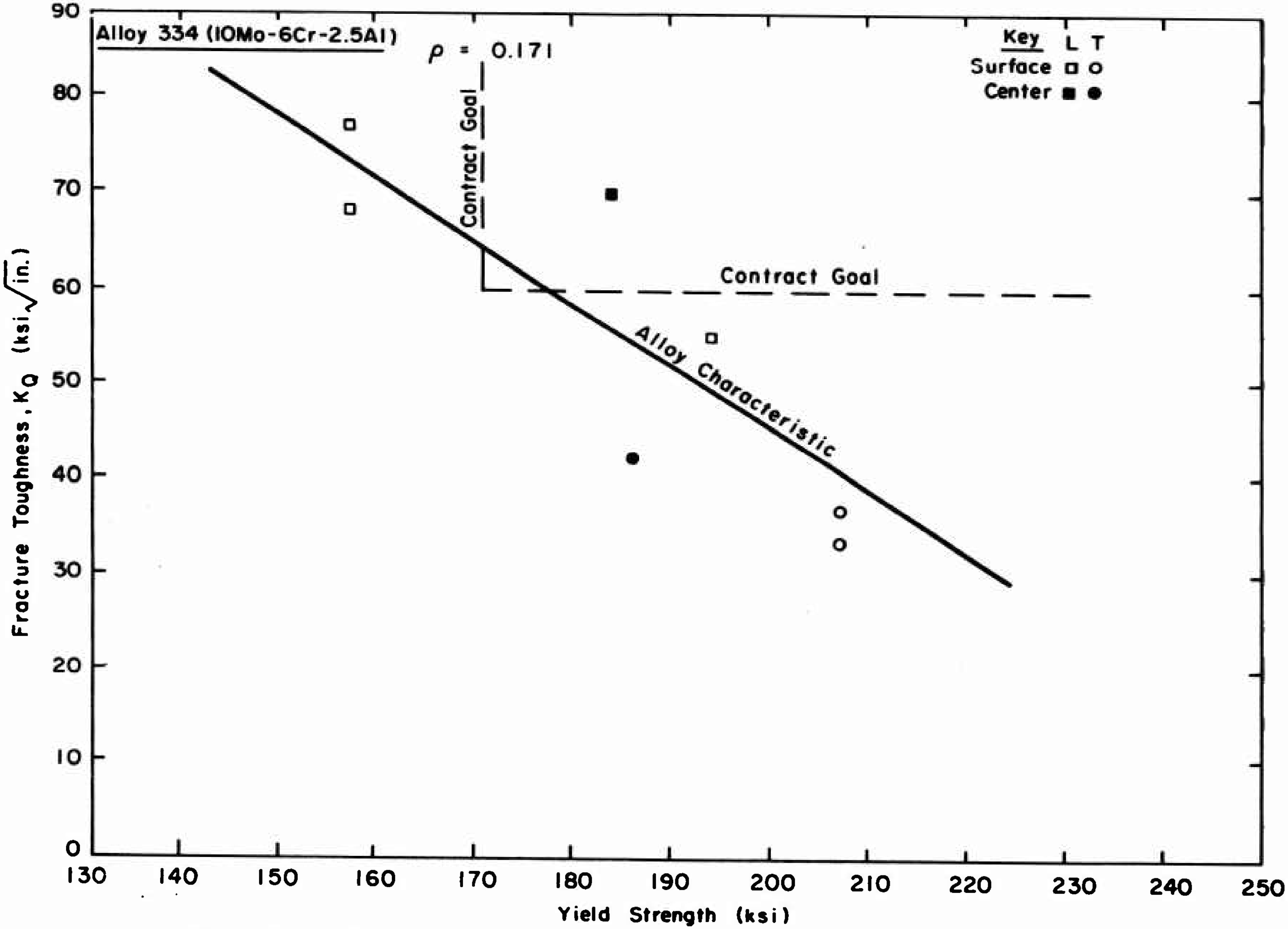


Figure 39 - Alloy 334. Fracture toughness-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

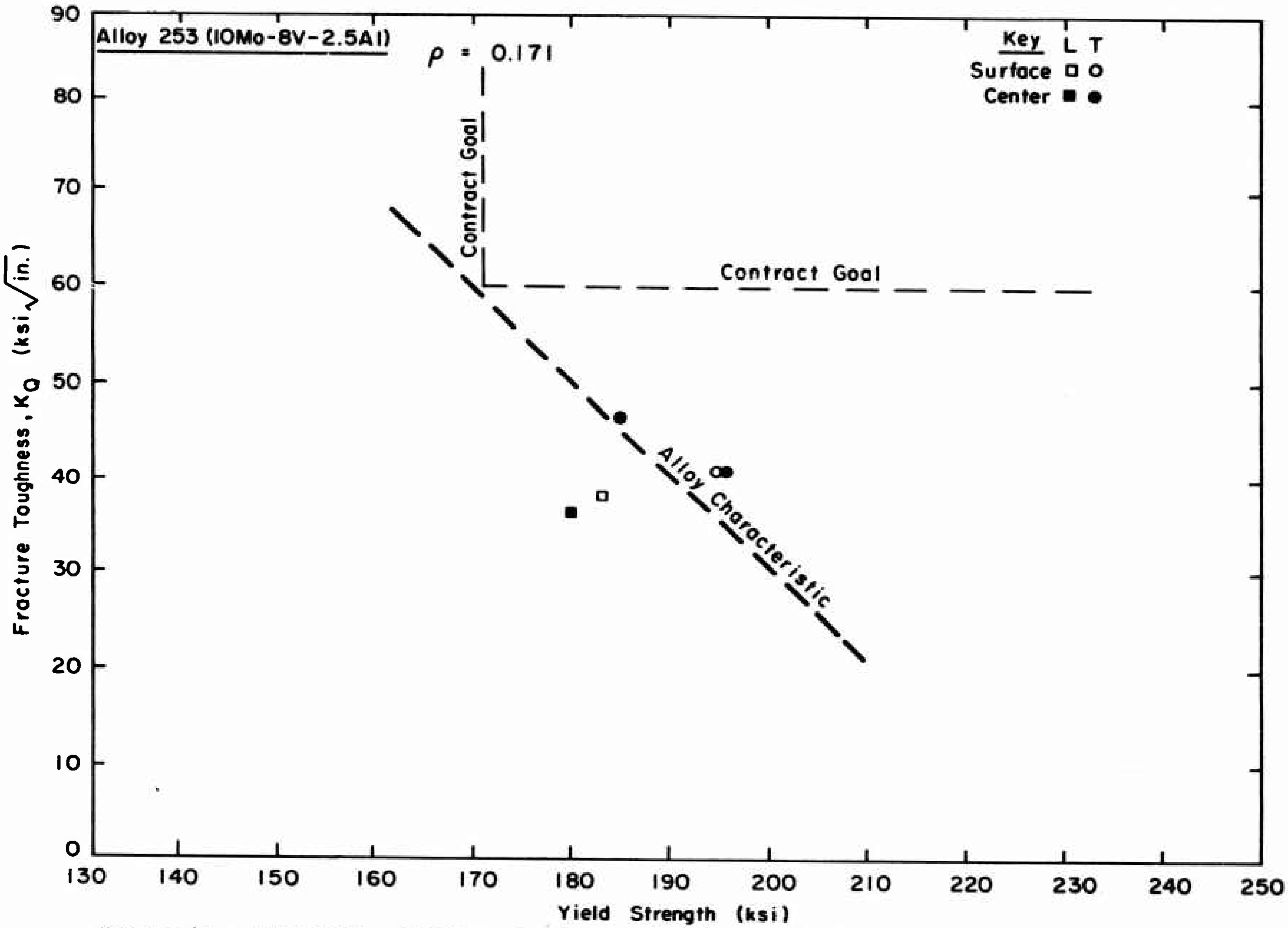


Figure 40 - Alloy 253. Fracture toughness-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

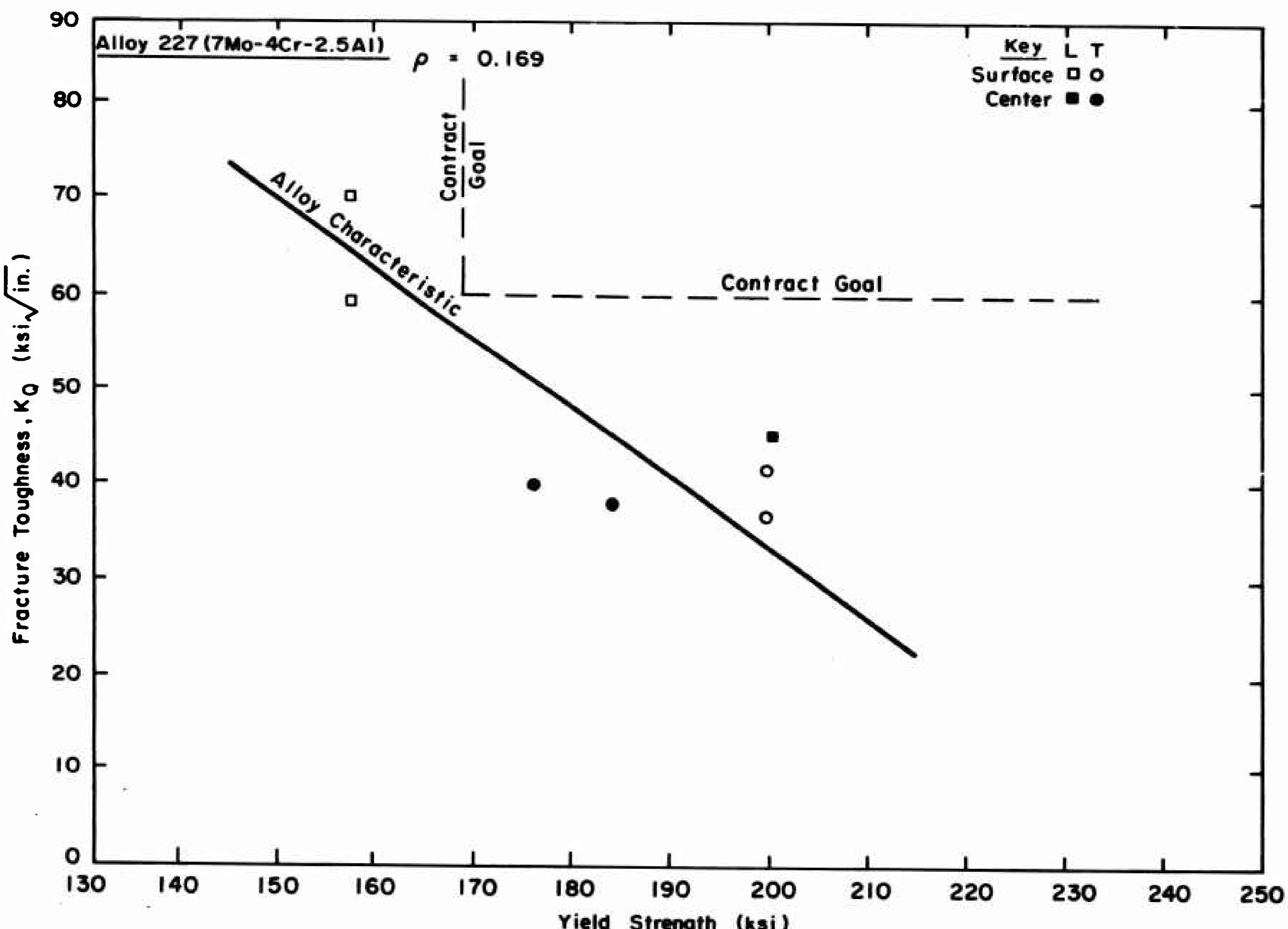


Figure 41 - Alloy 227. Fracture toughness-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

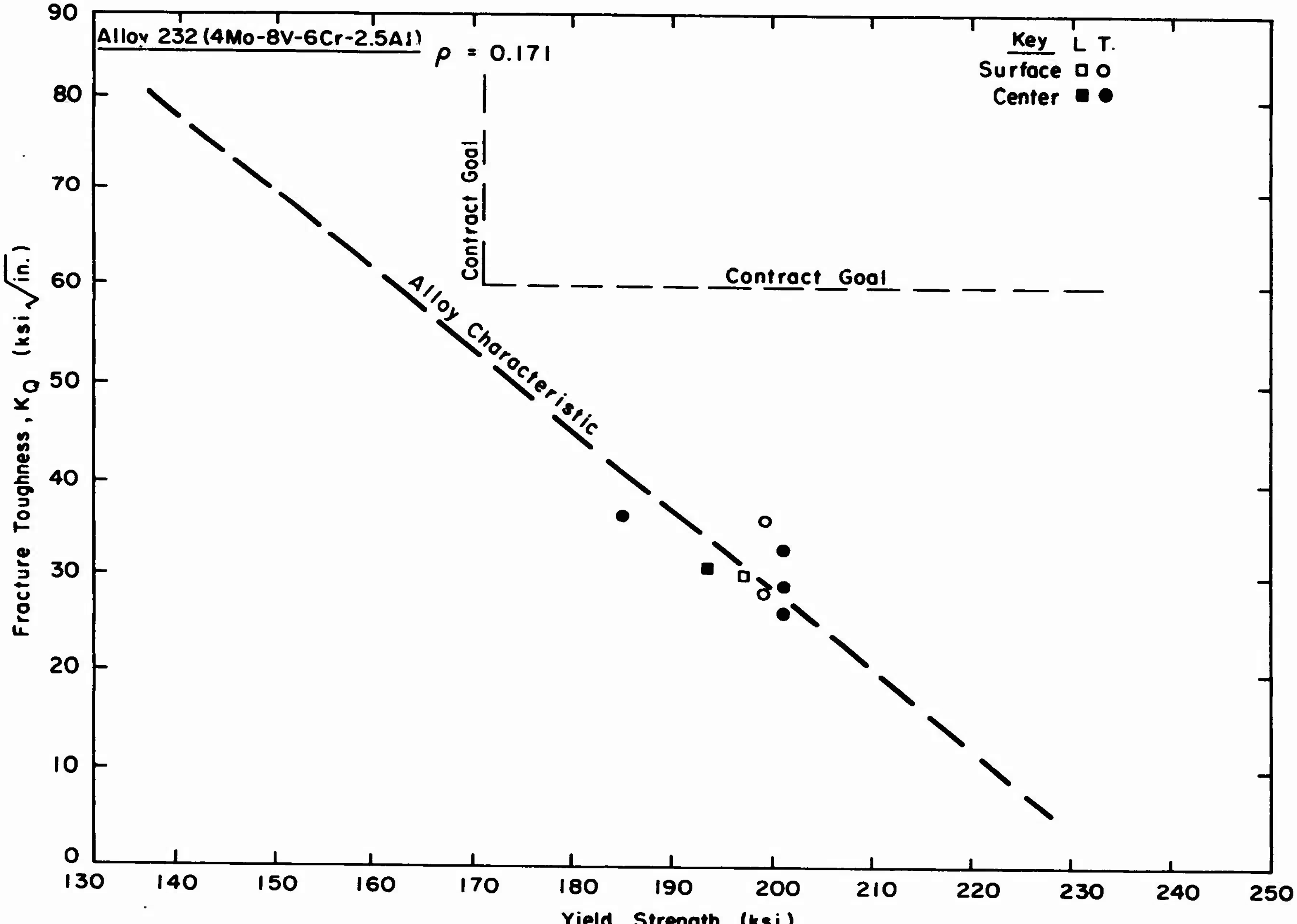


Figure 42 - Alloy 232. Fracture toughness-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

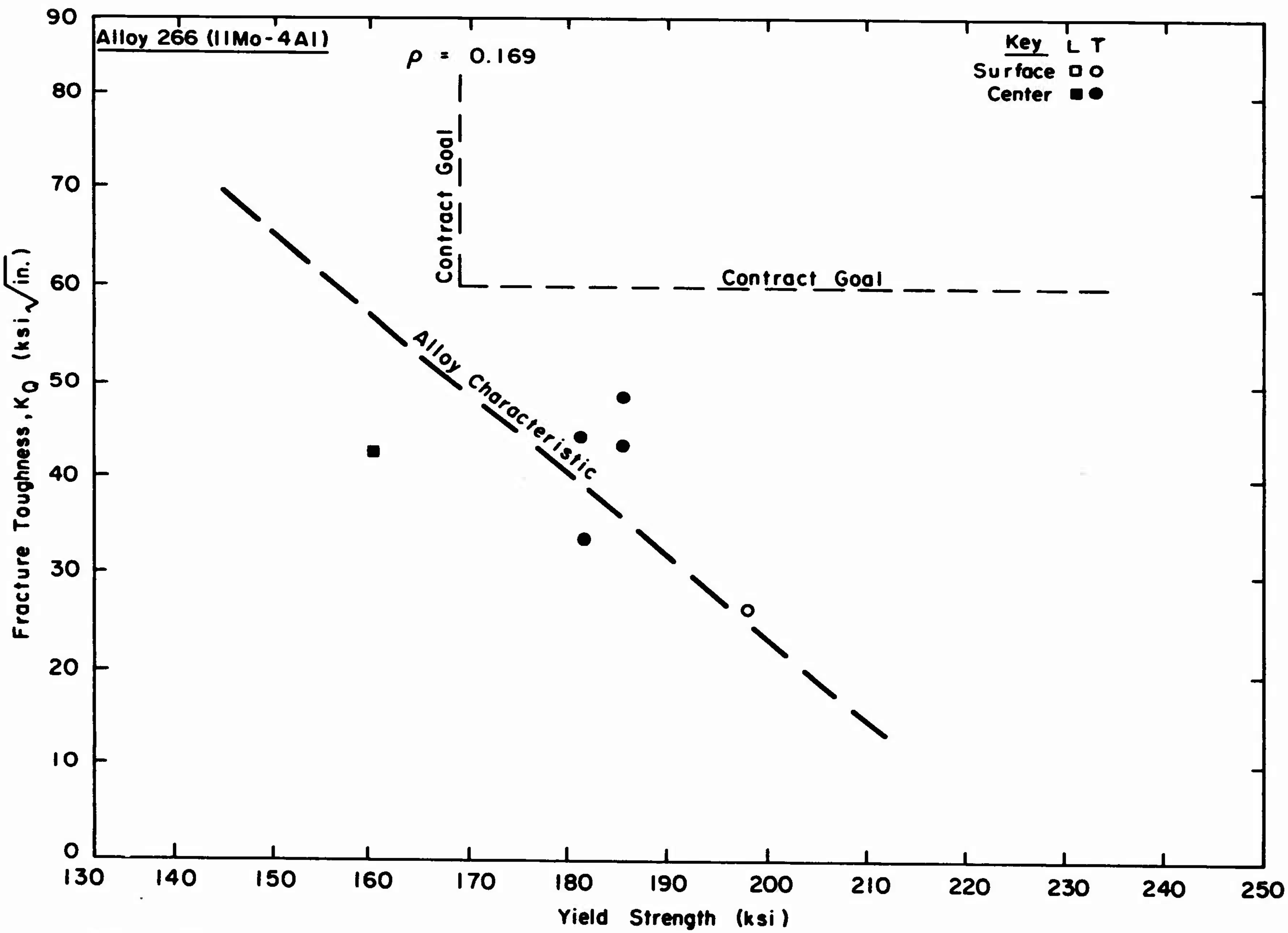


Figure 43 - Alloy 266. Fracture toughness-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

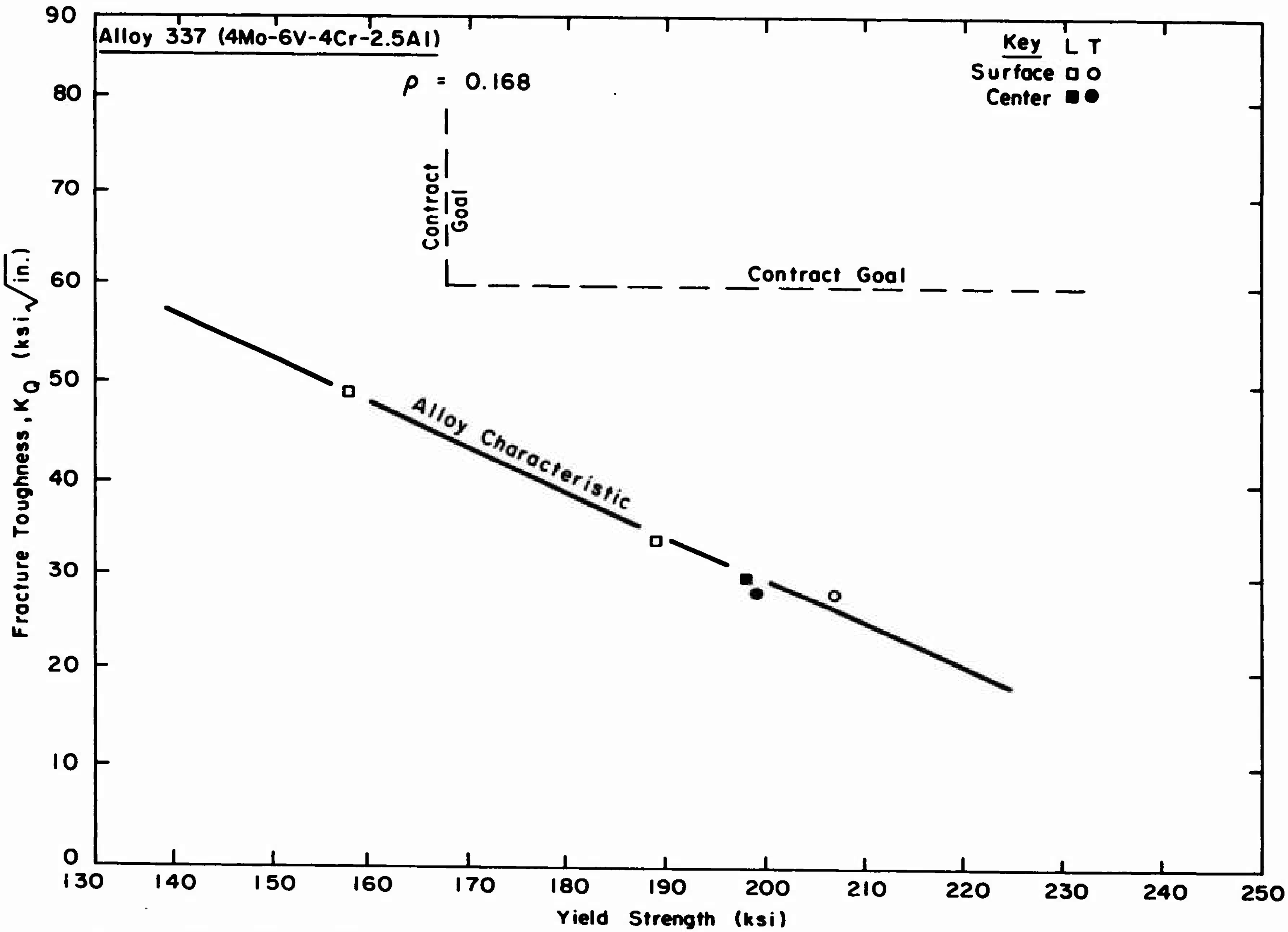


Figure 44 - Alloy 337. Fracture toughness-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

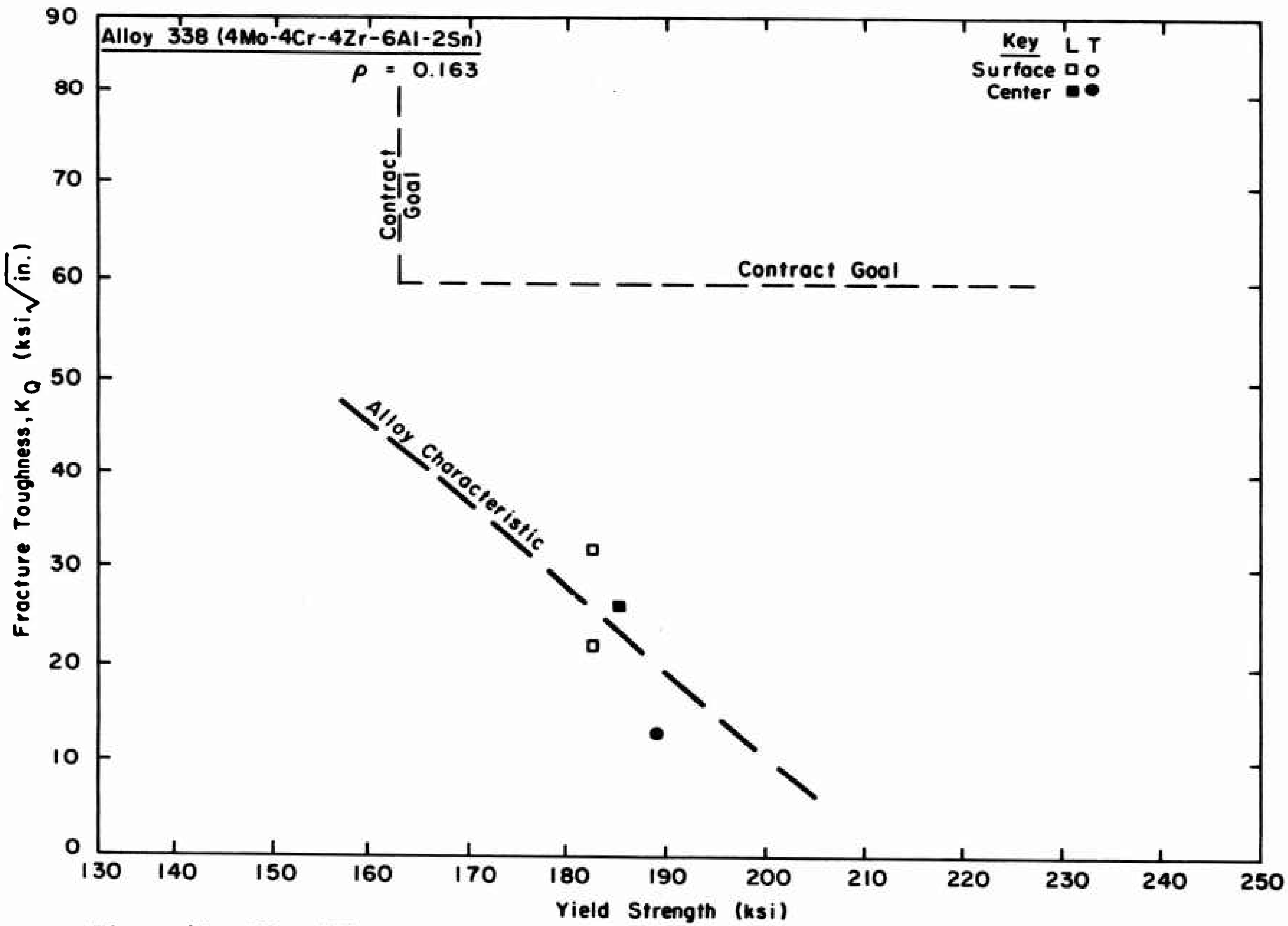


Figure 45 - Alloy 338. Fracture toughness-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

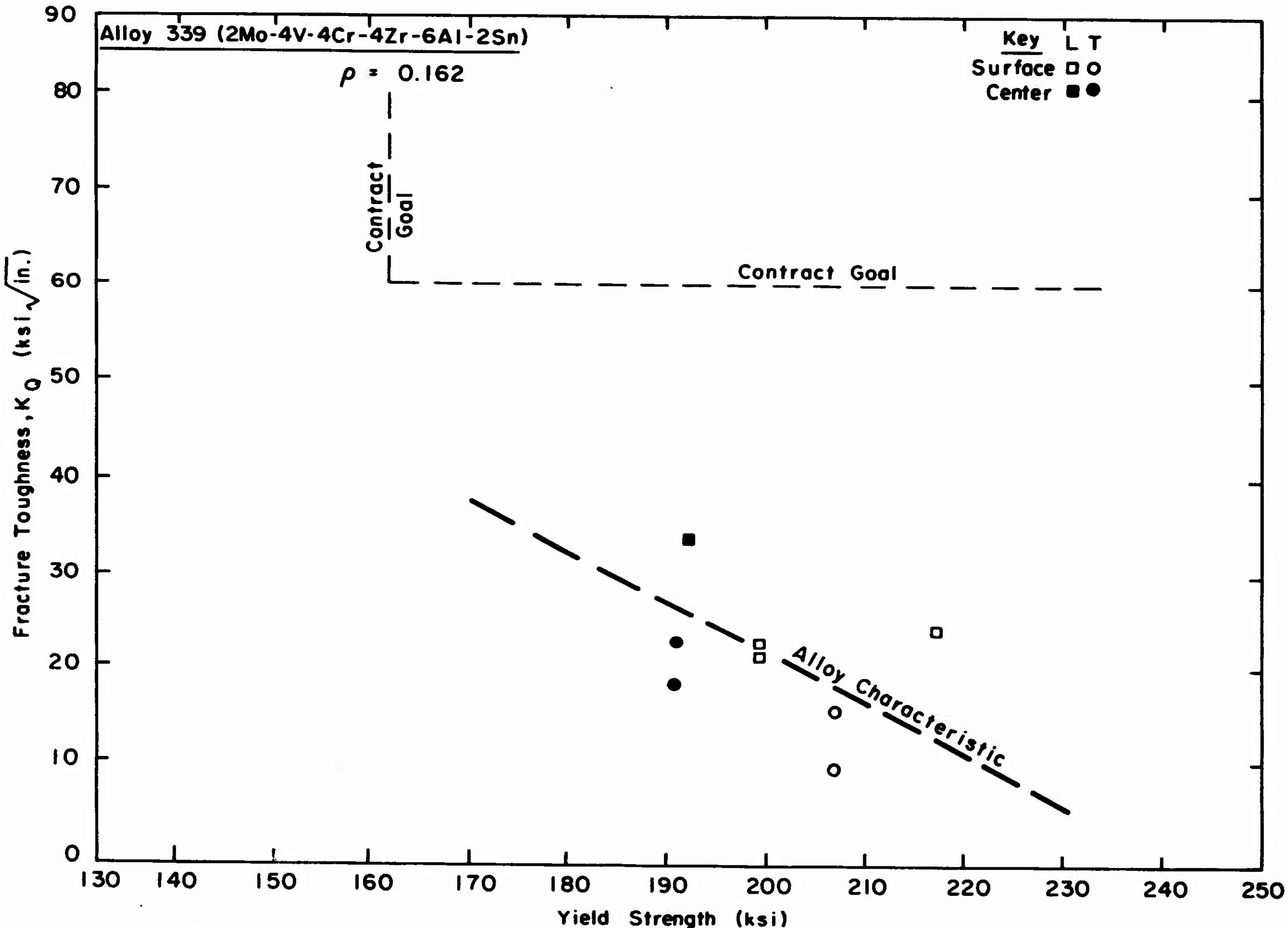


Figure 46 - Alloy 339. Fracture toughness-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

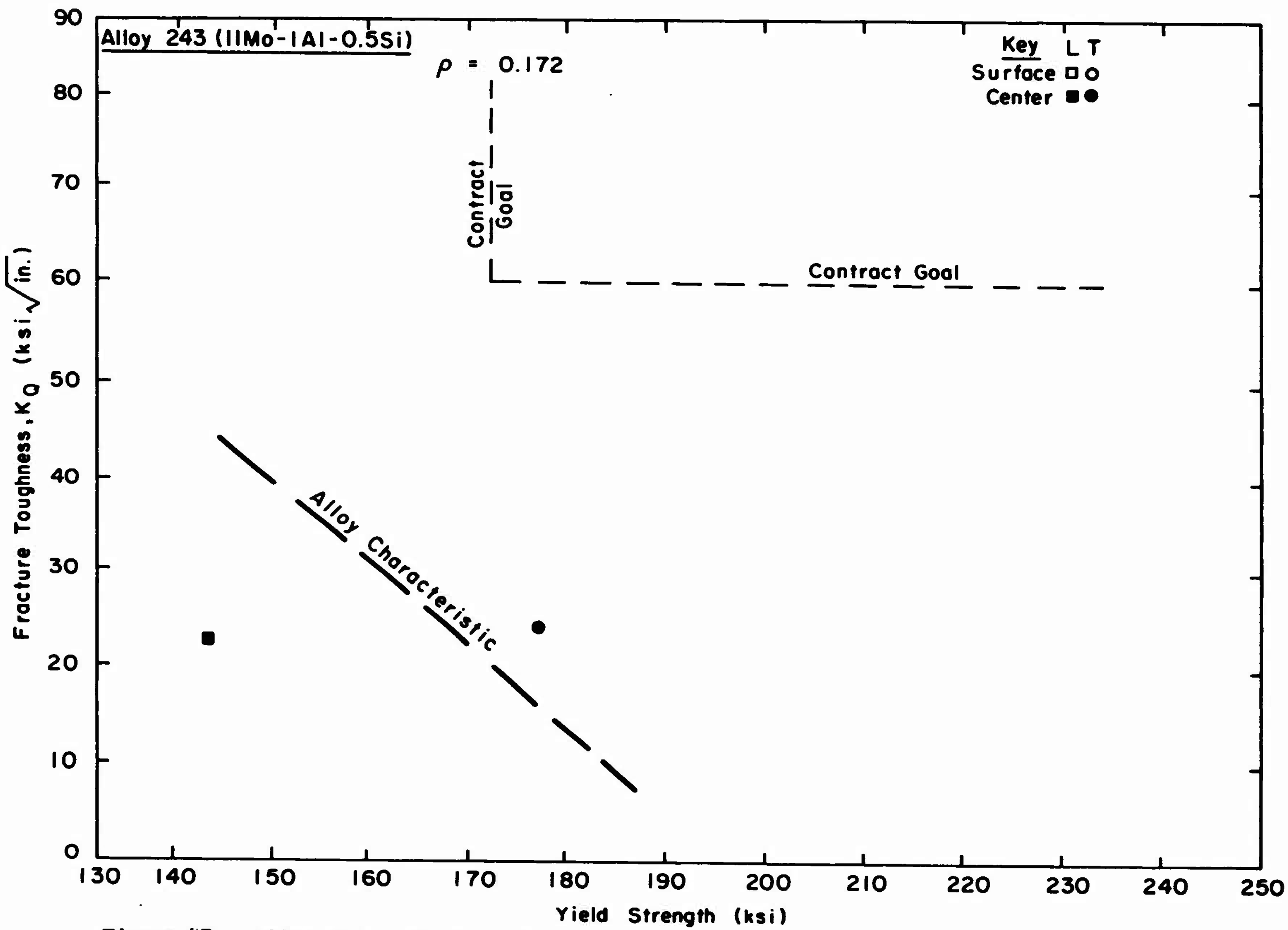


Figure 47 - Alloy 243. Fracture toughness-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

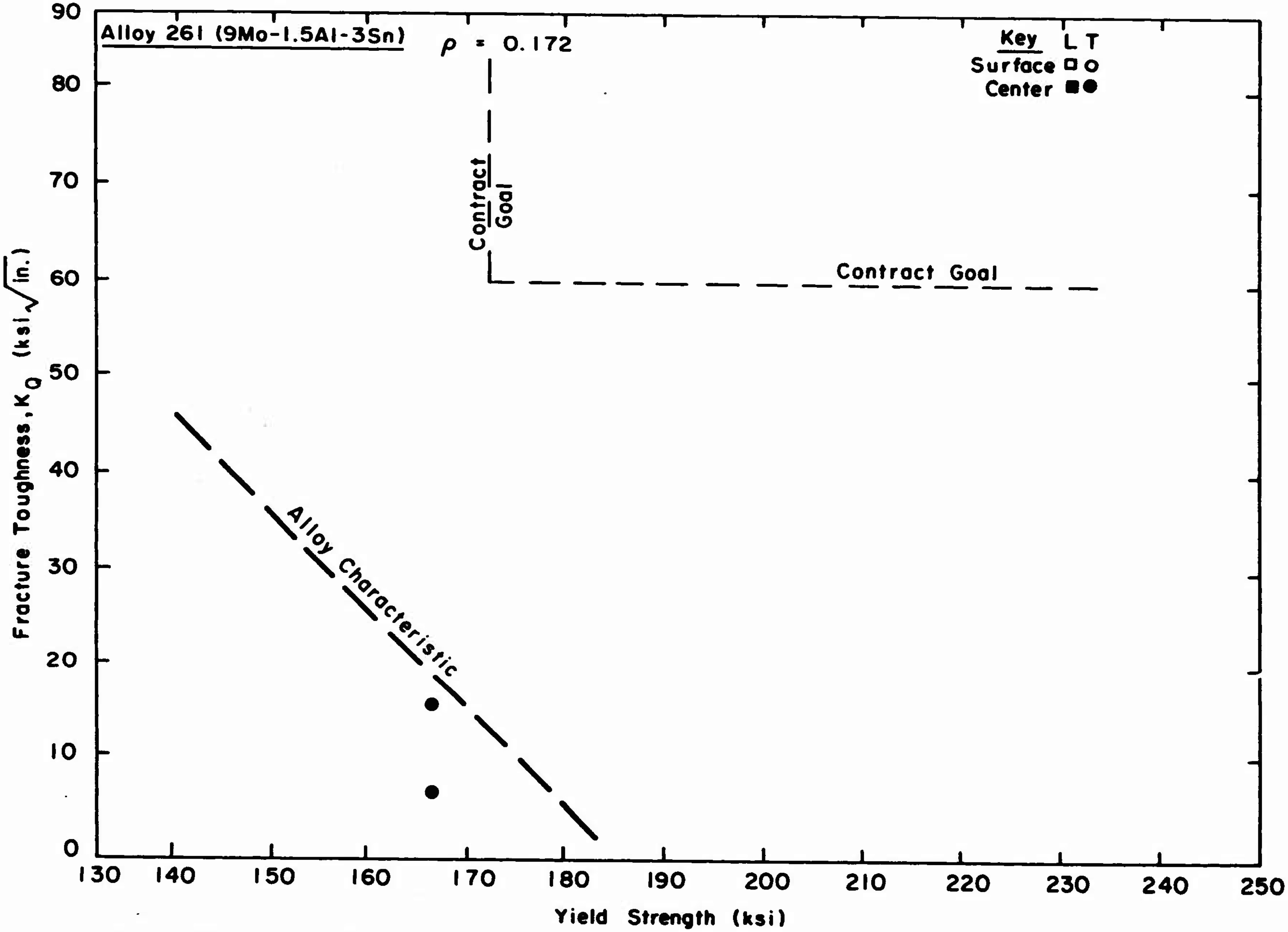


Figure 48 - Alloy 261. Fracture toughness-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

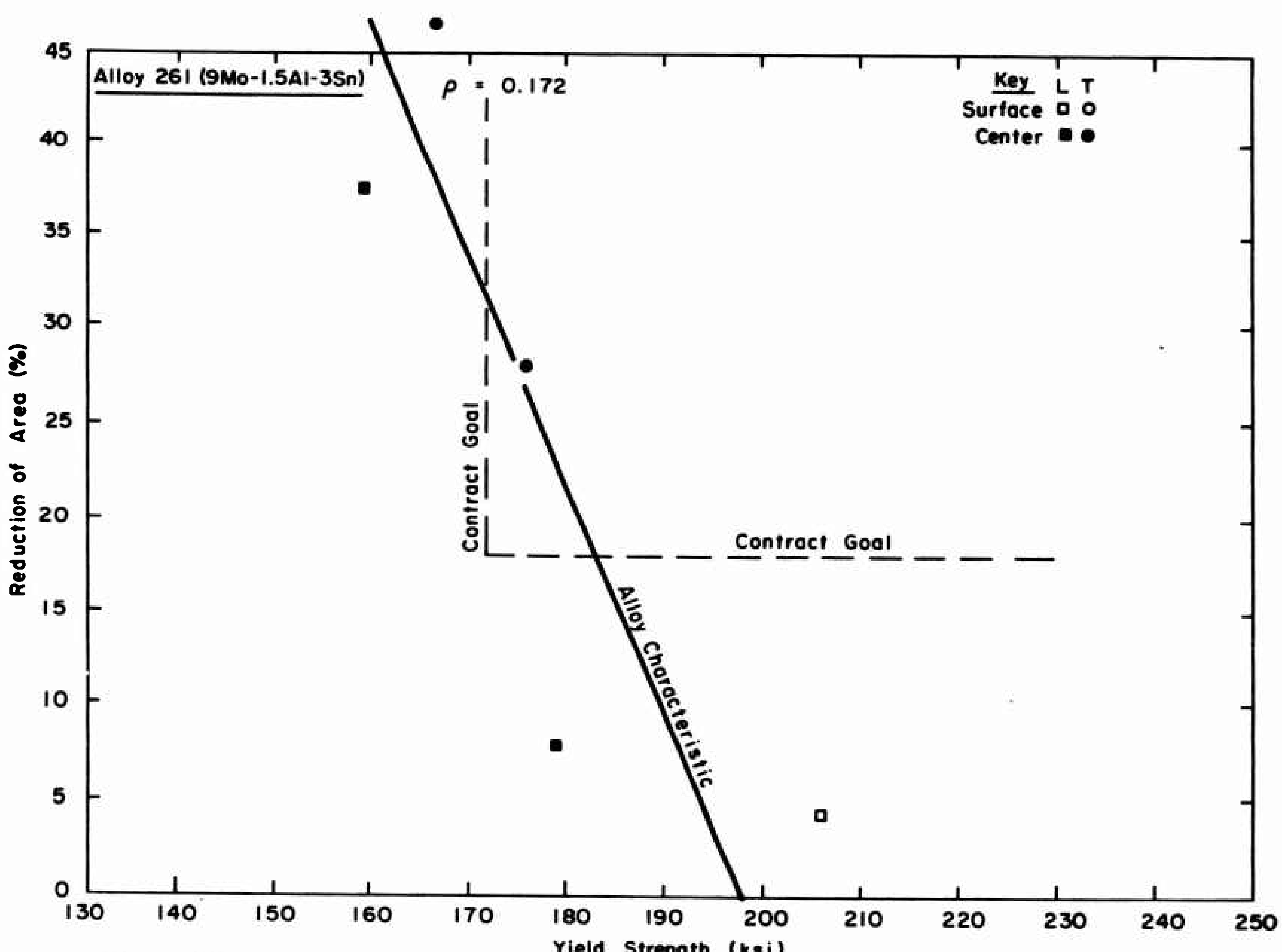


Figure 49 - Alloy 261. Ductility-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

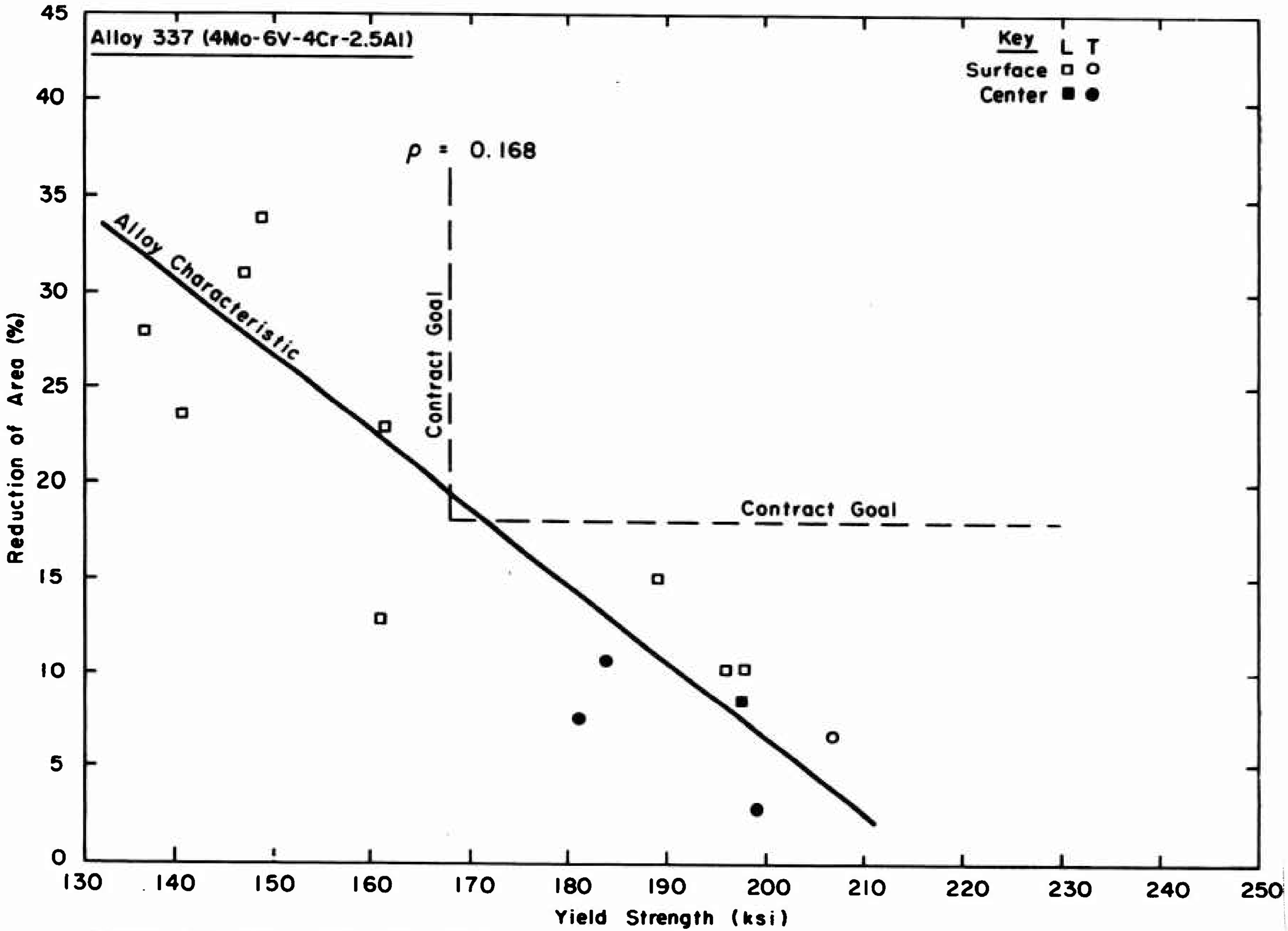


Figure 50- Alloy 337. Ductility-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

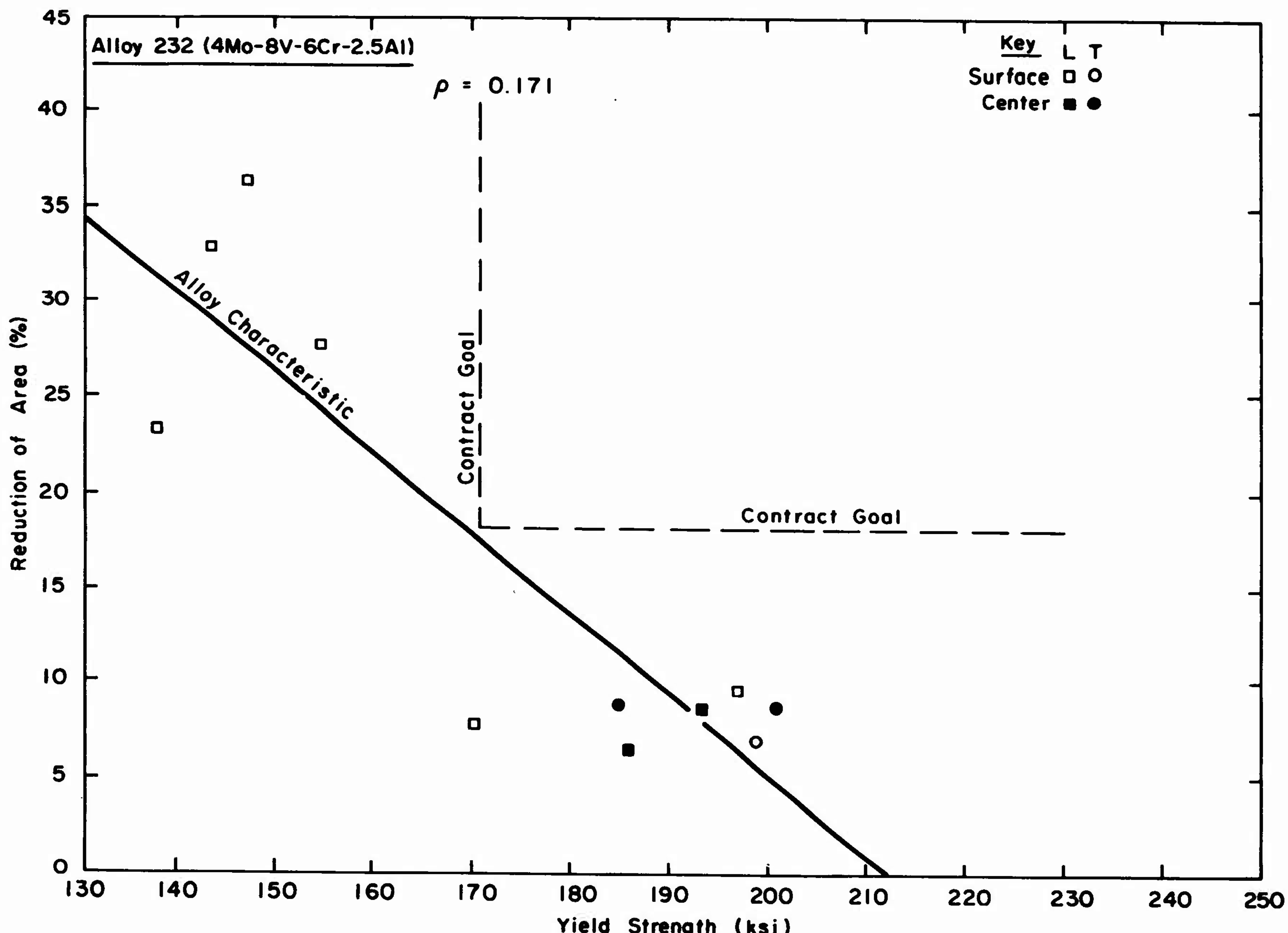


Figure 51 - Alloy 232. Ductility-yield strength characteristic alloy trend lines.

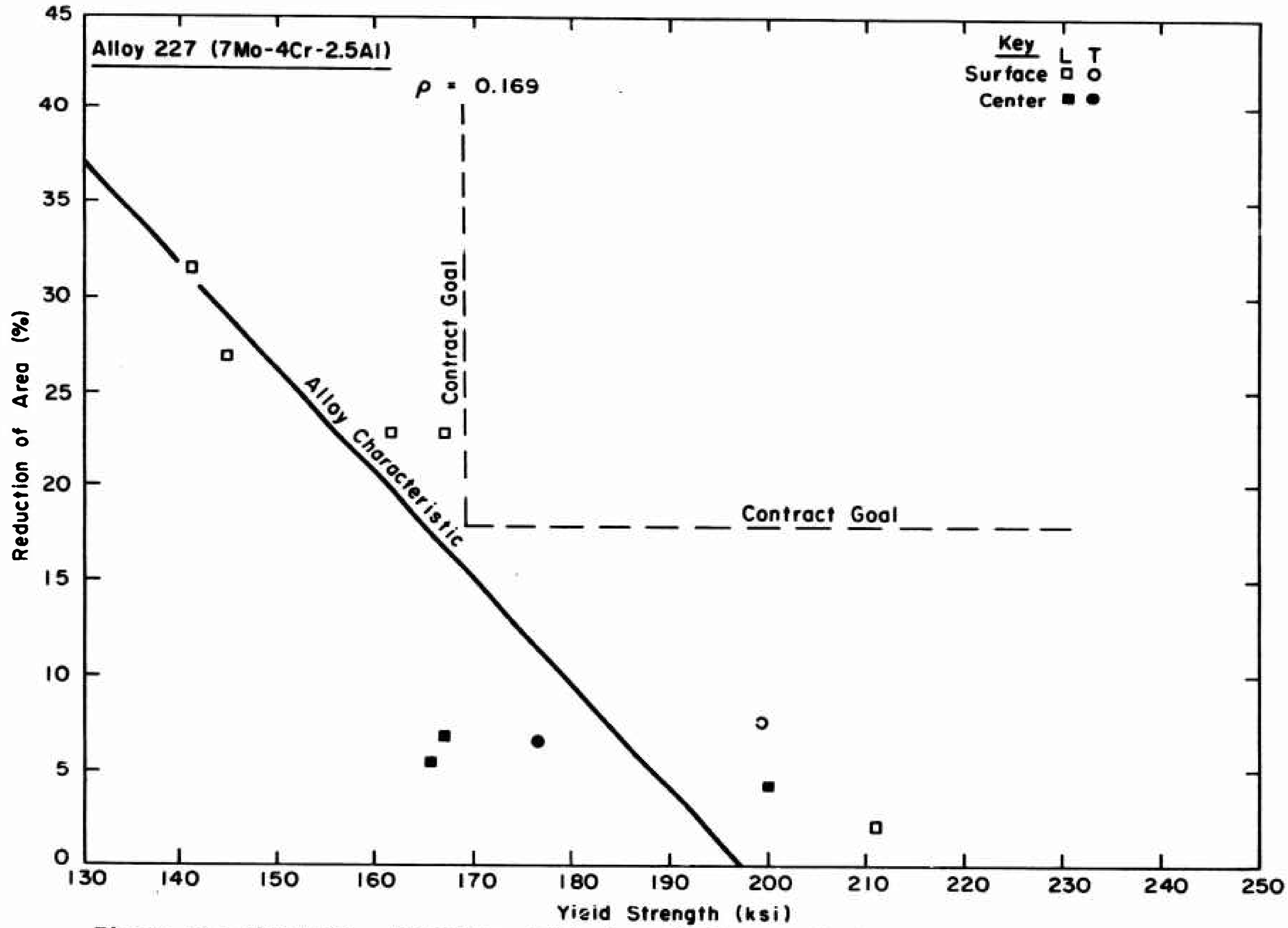


Figure 52 - Alloy 227. Ductility-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

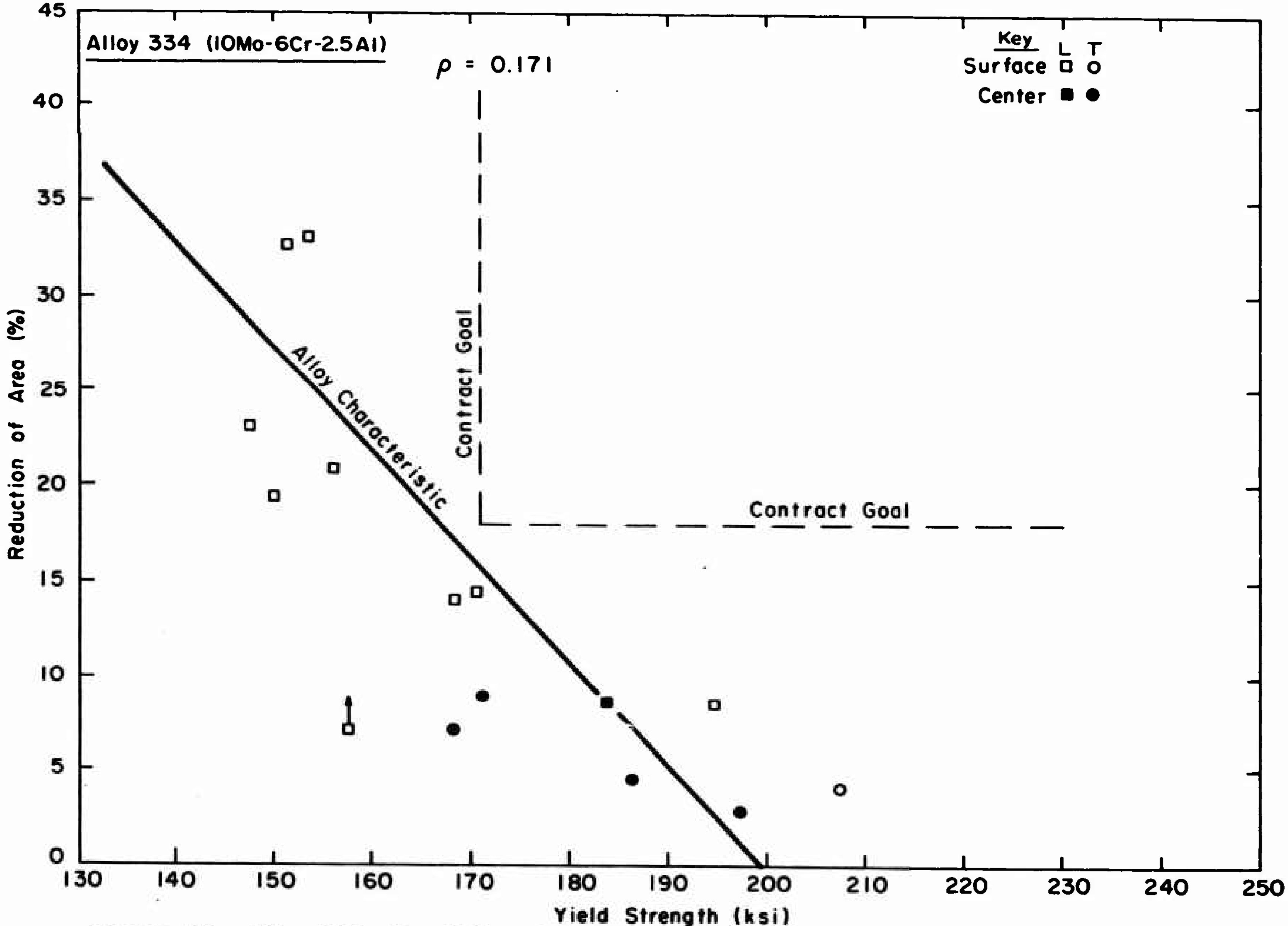


Figure 53 - Alloy 334. Ductility-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

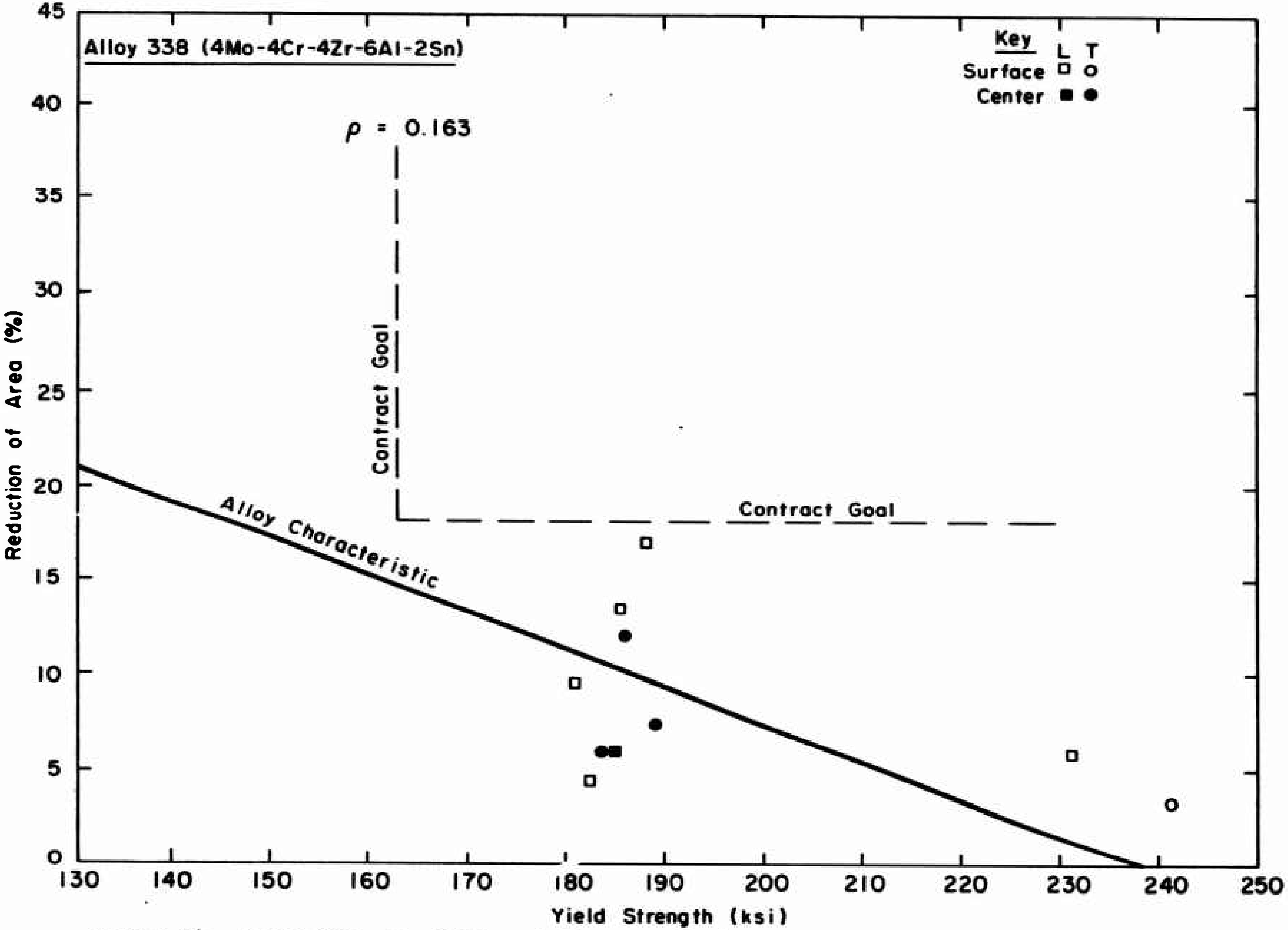


Figure 54 - Alloy 338. Ductility-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

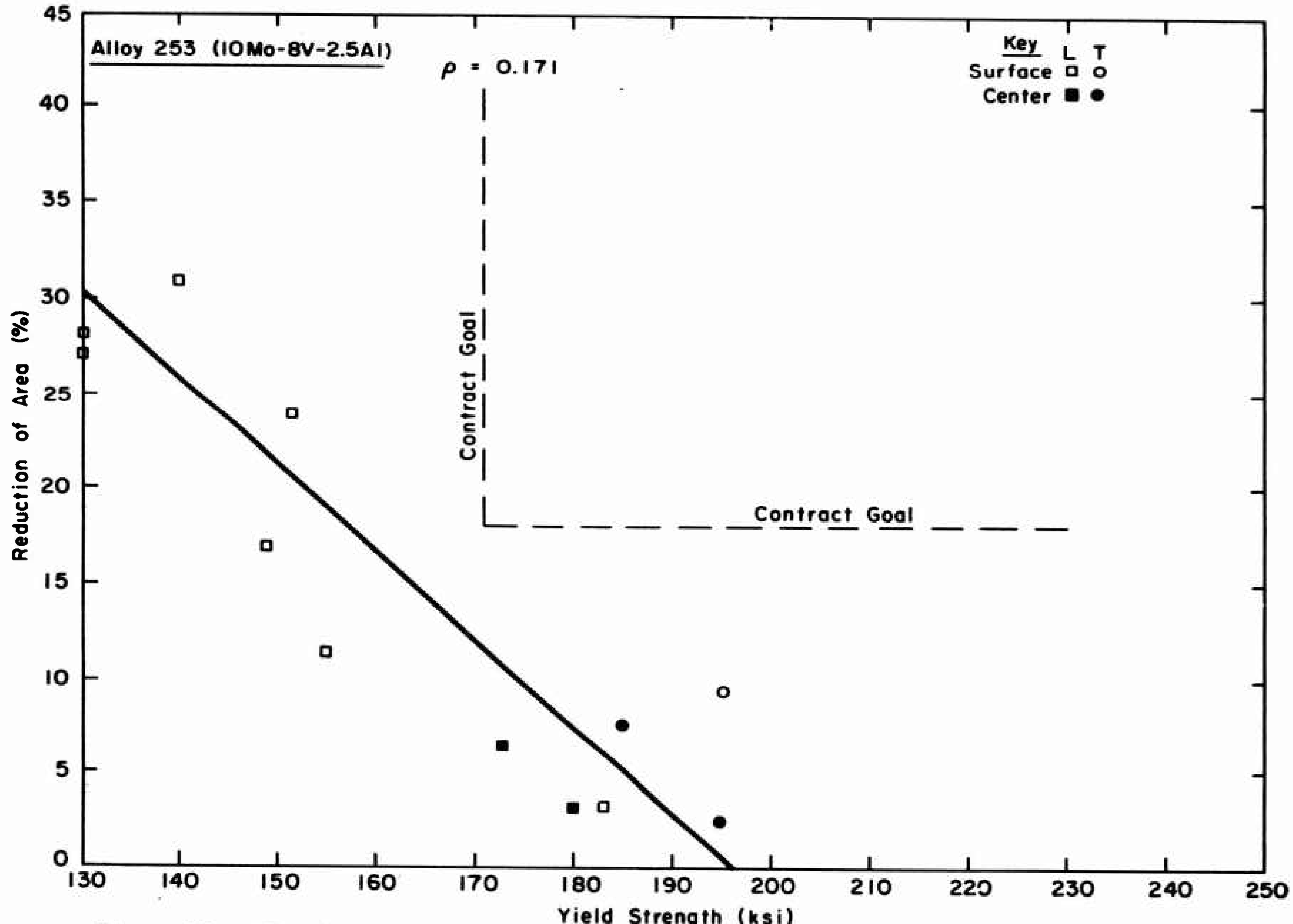


Figure 55 - Alloy 253. Ductility-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

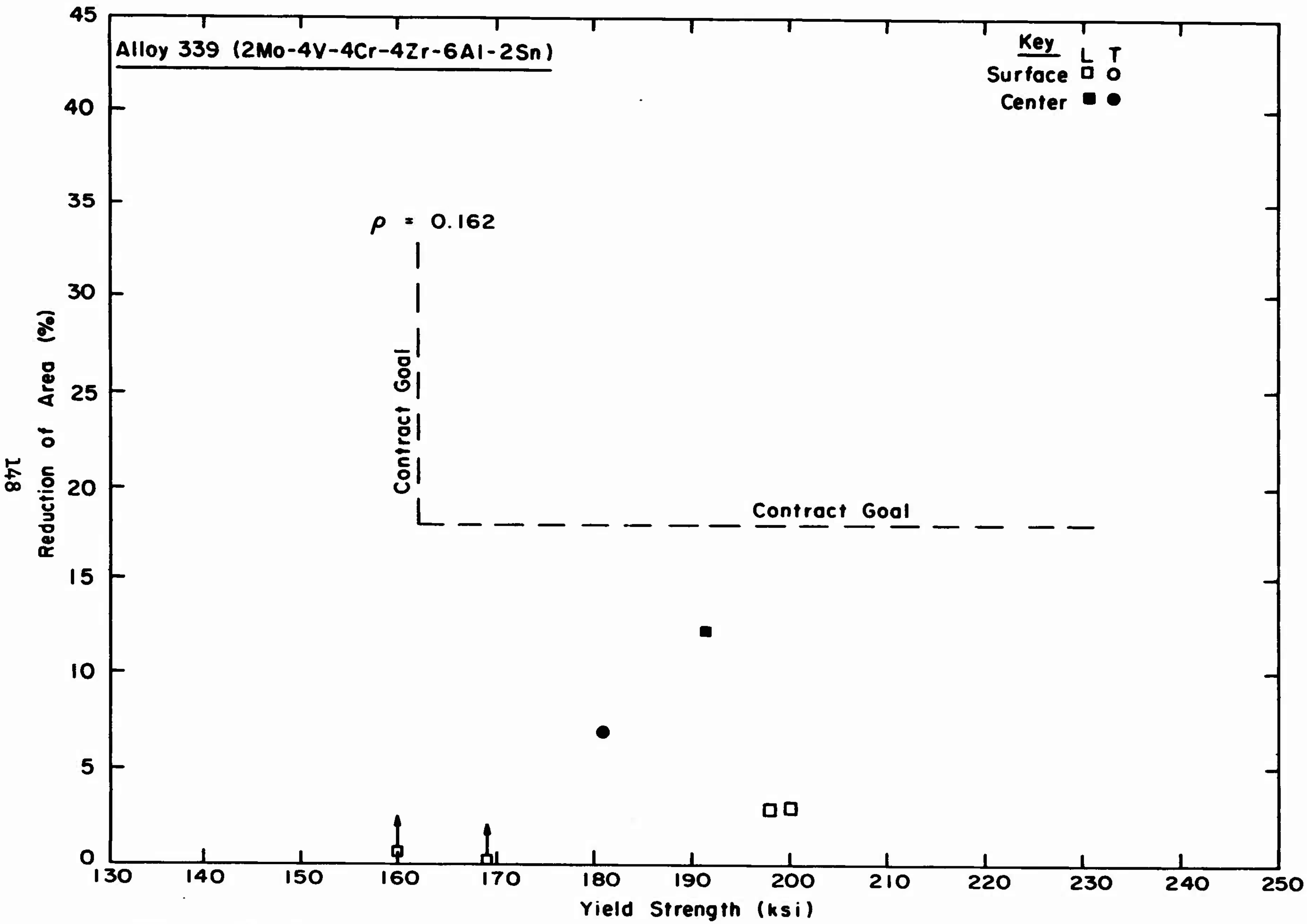


Figure 56 - Alloy 339. Ductility-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

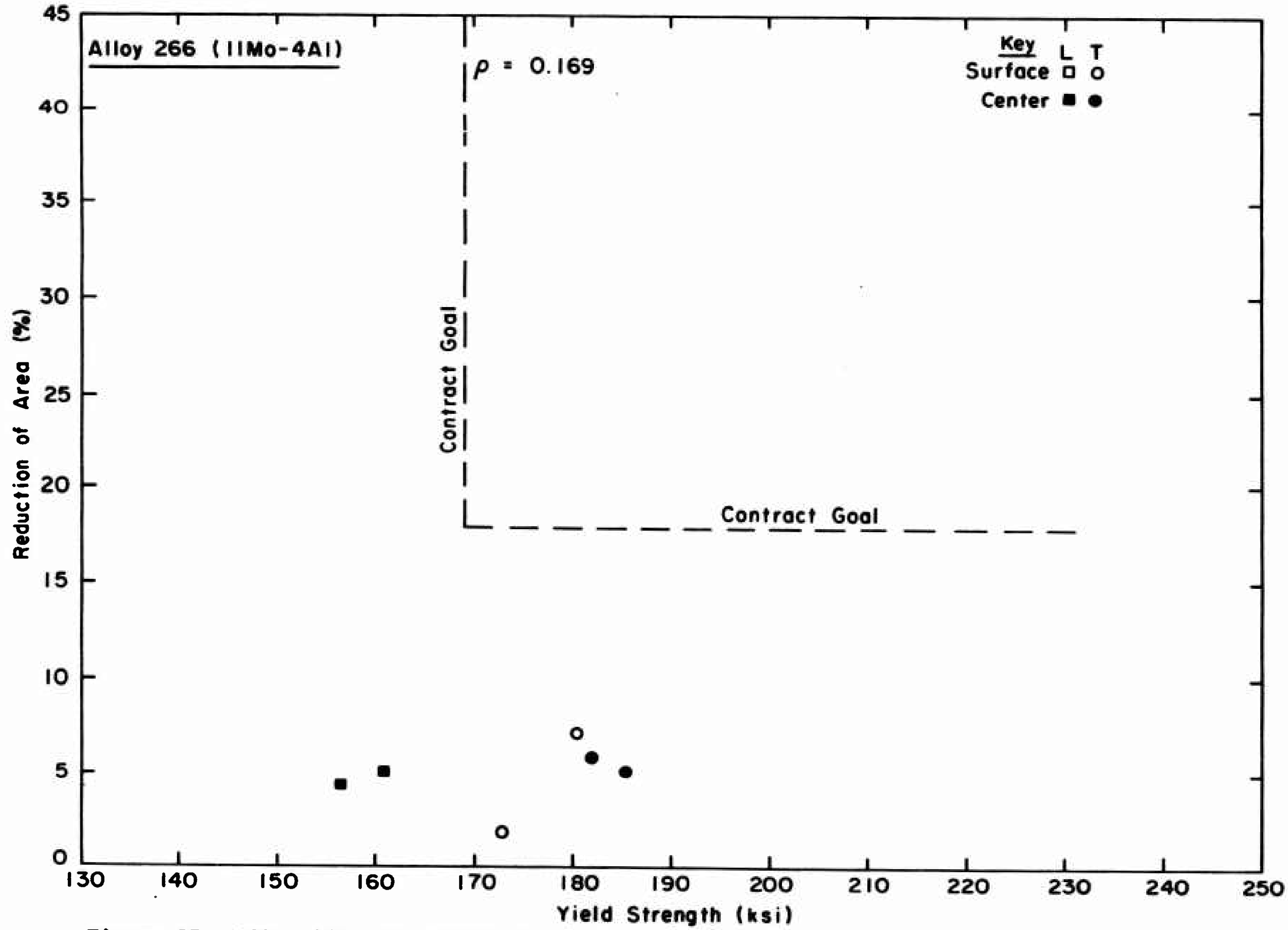


Figure 57 - Alloy 266. Ductility-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.

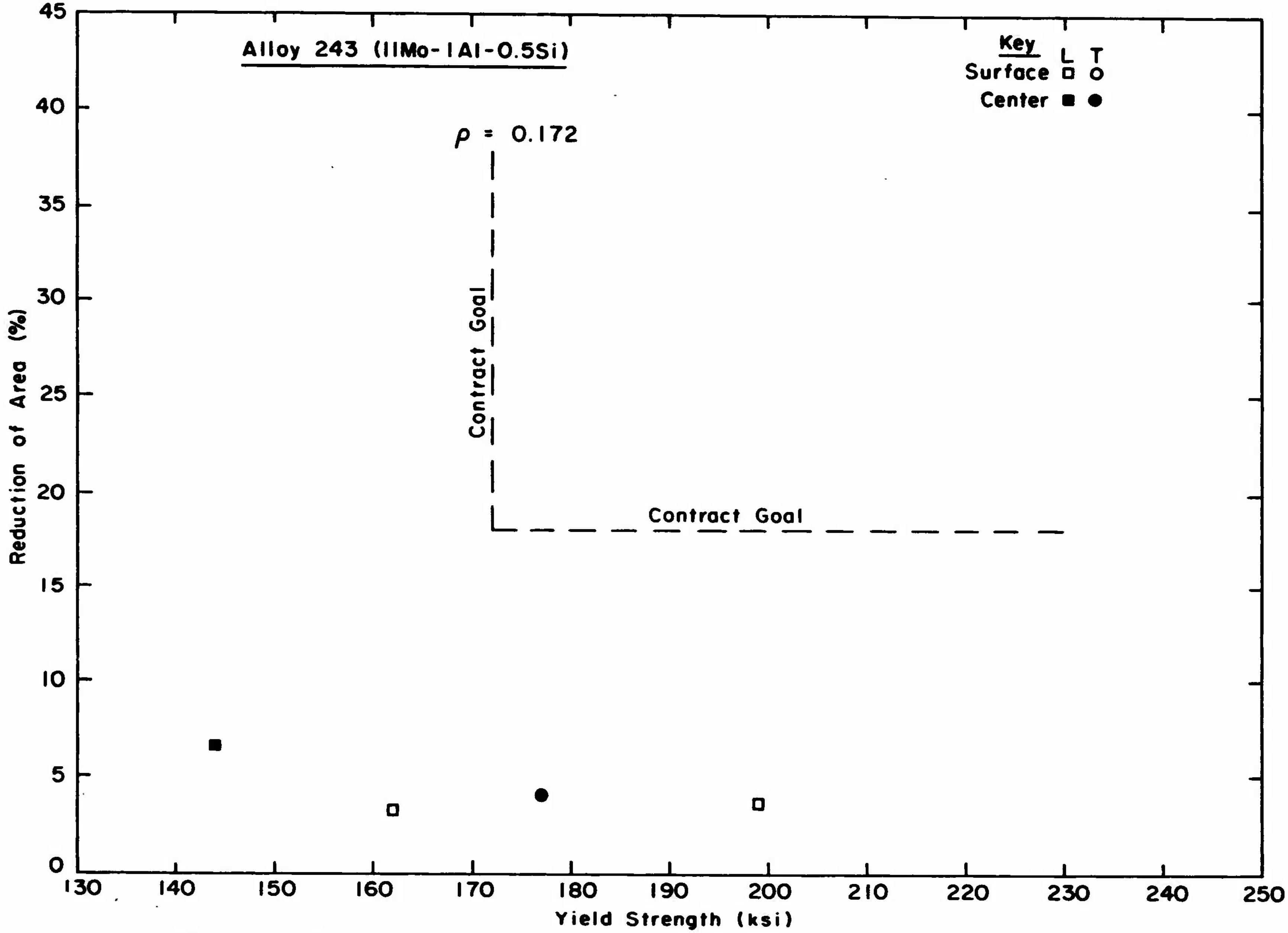
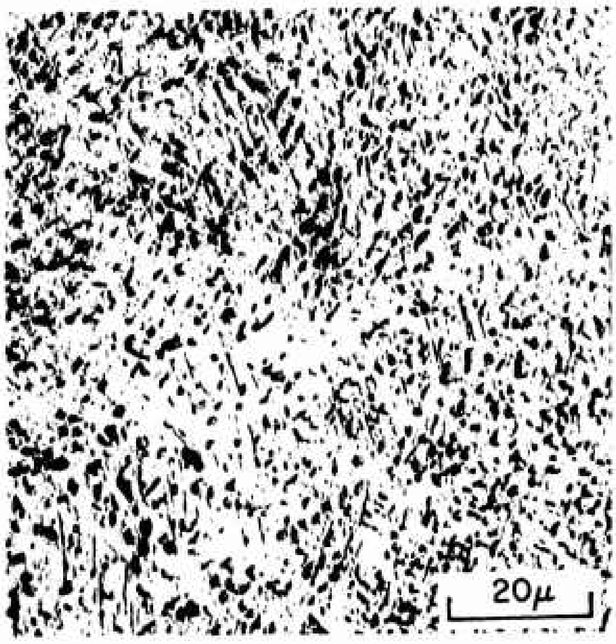
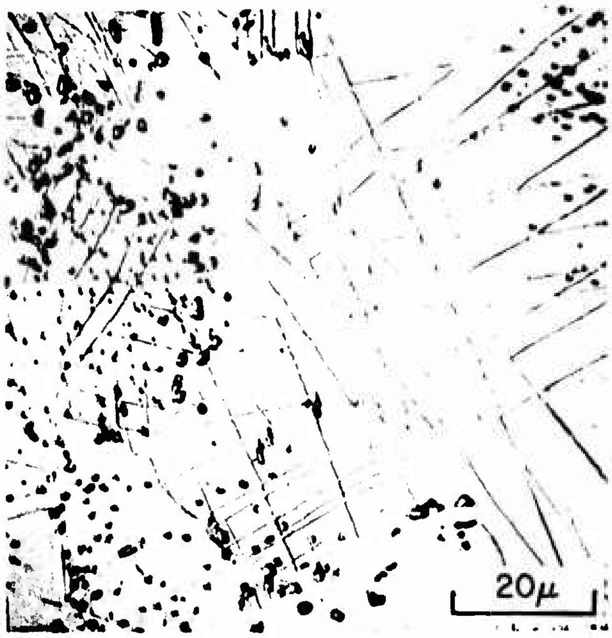


Figure 58 - Alloy 243 - Ductility-yield strength characteristic alloy trend lines. Defined using the data from Tables XX and XXI.



a



b

Fig. 59 - Microstructure as revealed by light microscopy in (a) Alloy 226 (12V-2.5Al) as solution treated and (b) Alloy 227 (7Mo-4Cr-2.5Al) as solution treated.

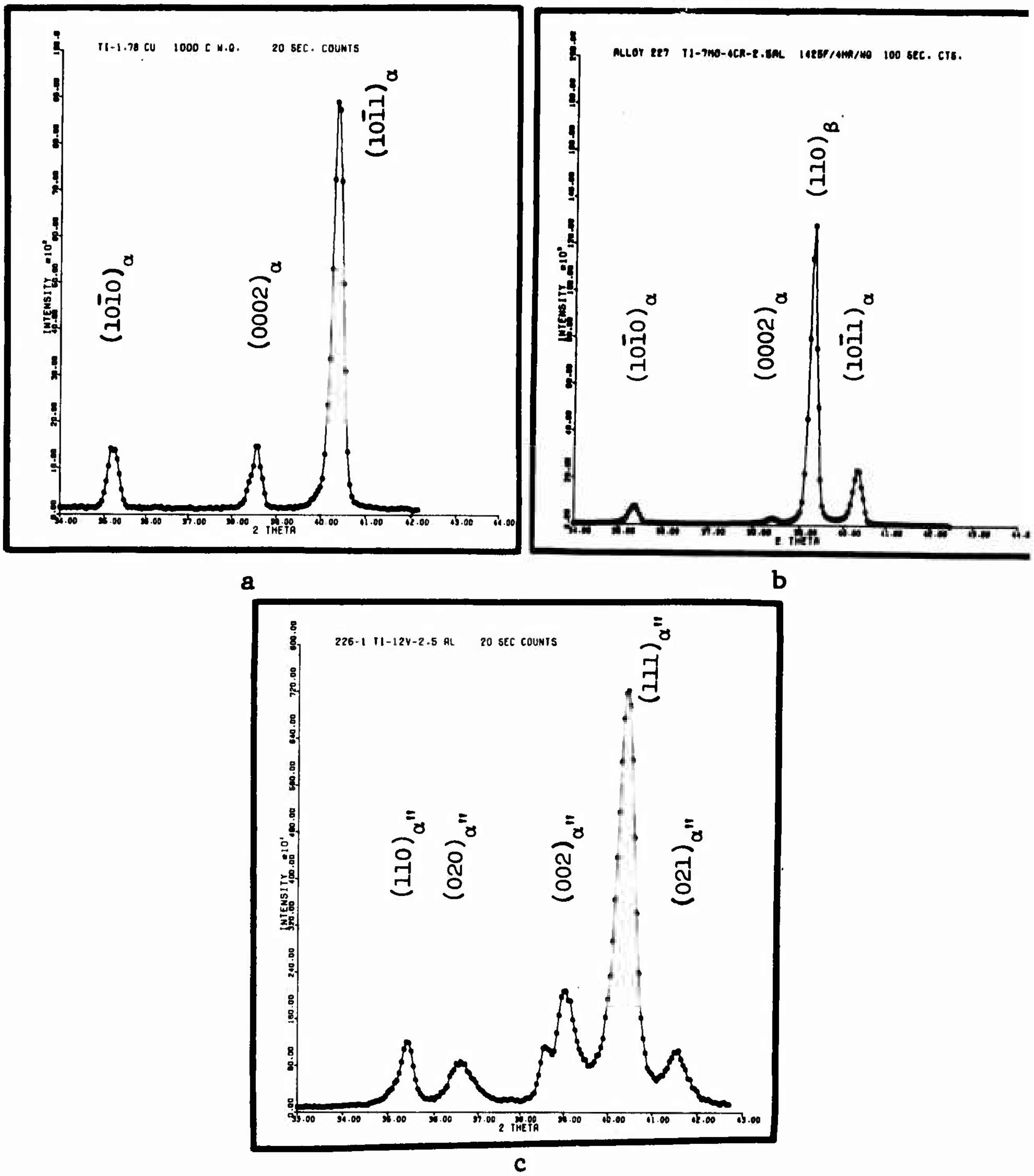


Fig. 60 - X-ray diffraction scans in the range of 34°-40° 2θ from (a) hexagonal martensite or primary α; (b) hexagonal martensite or primary α plus β; (c) orthorhombic martensite (α'').

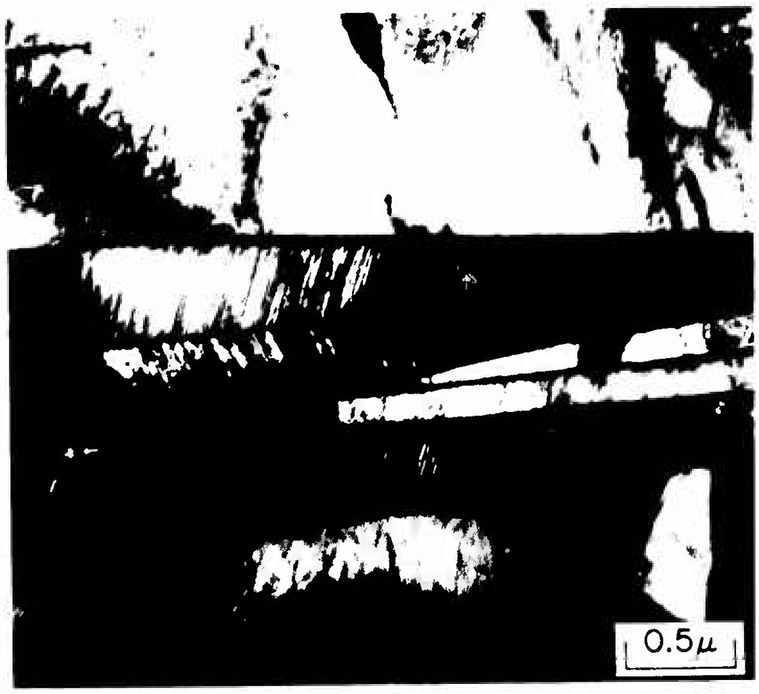


Fig. 61 - Transmission electron micrograph of Alloy 227 (7Mo-4Cr-2.5Al) as solution treated showing α" which has spontaneously transformed to an fcc martensite during thinning.

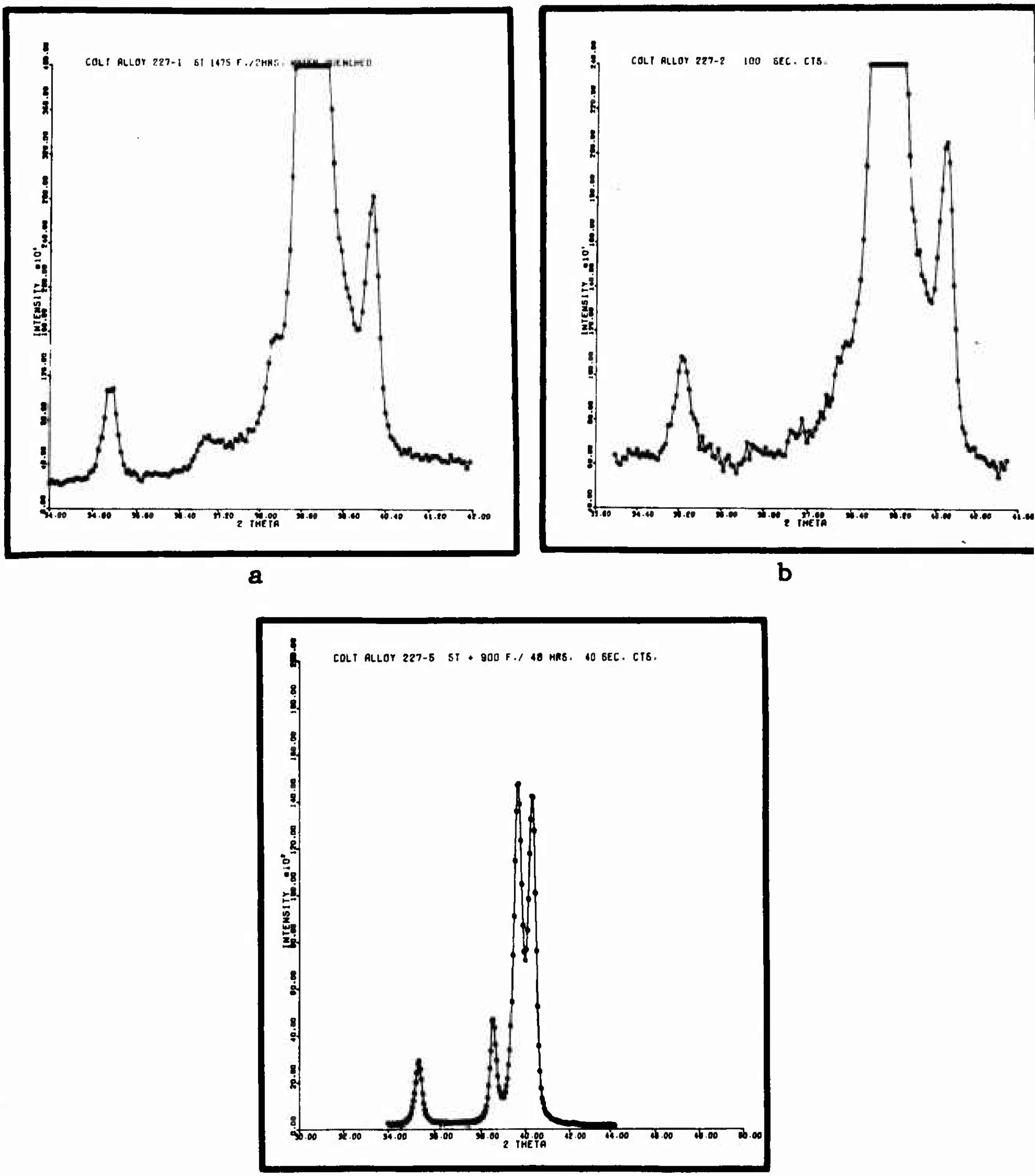
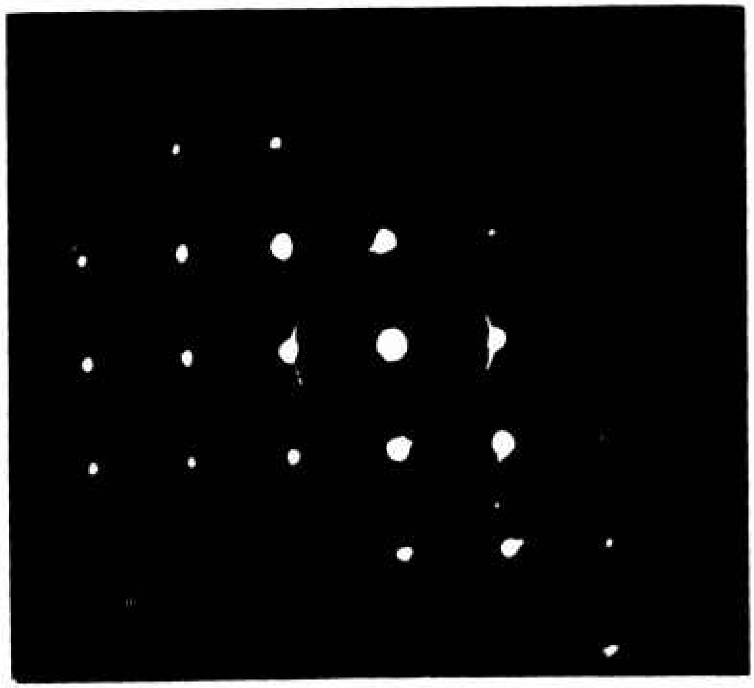
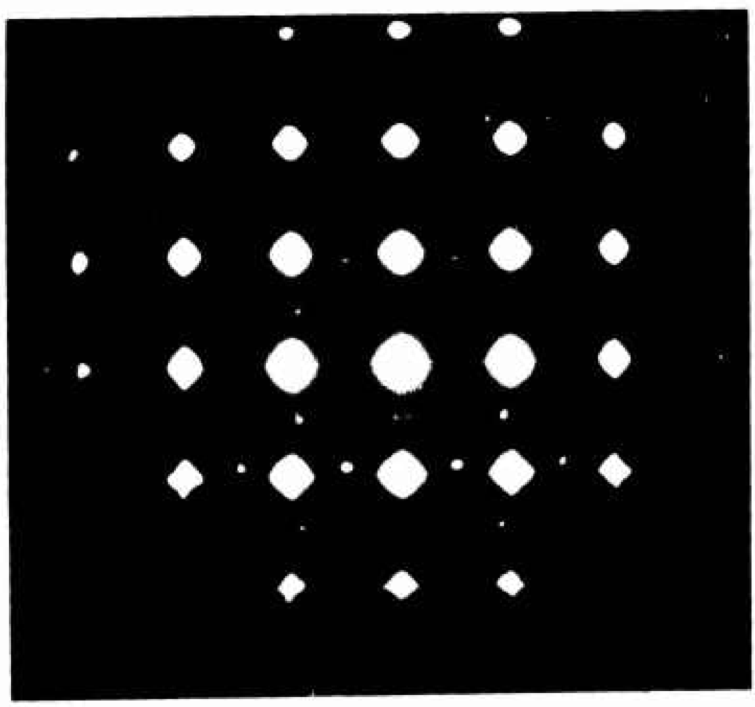


Fig. 62 - X-ray diffraction scans illustrating reversion of α" to β during early stages of aging Alloy 227 (7Mo-4Cr-2.5Al). (a) α" in as solution treated condition, (b) α+β in sample aged 1 minute at 900F, (c) α+β in sample aged 48 hours at 900F. Note increase in α-line intensity and change in β-line position due to alloy partitic compared to sample aged for 1 minute.

Fig. 63 - Transmission electron micrograph of Alloy 227 (7Mo-4Cr-2.5Al) solution treated and aged 6 minutes at 900F. Microstructure consists of α precipitates in β matrix.

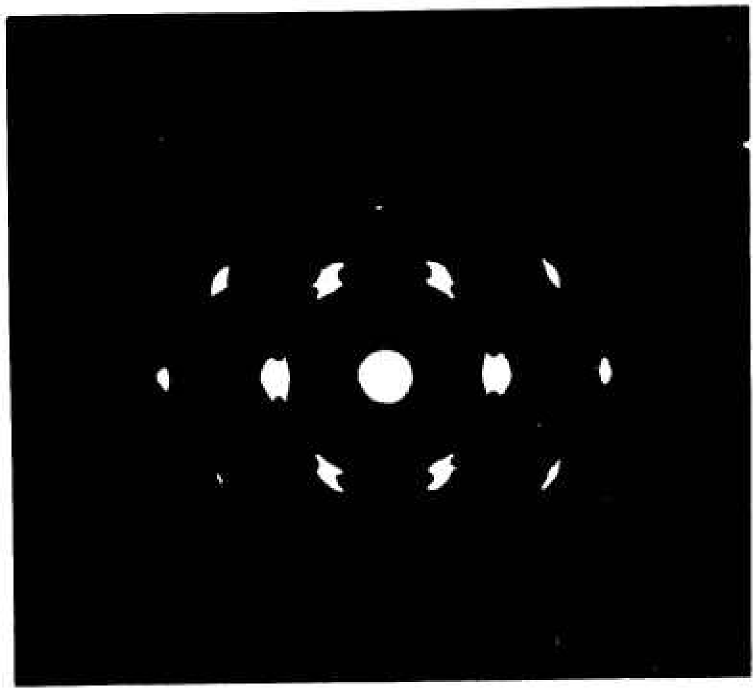


a

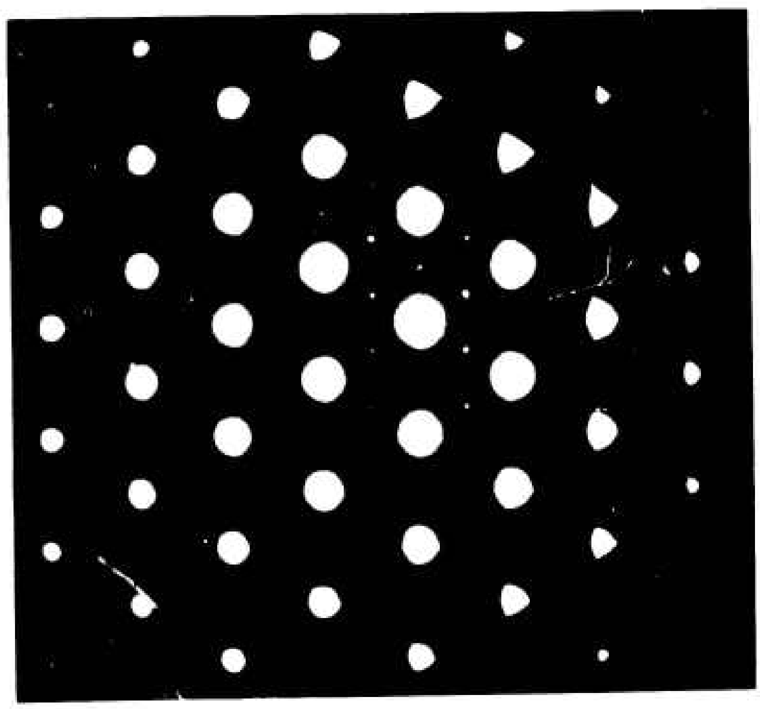


b

Fig. 64 - Selected area diffraction patterns from TEM samples in which α-phase has precipitated in a beta matrix. (a) $[100]_\beta$ zone in Alloy 227 (7Mo-4Cr-2.5Al) solution treated and aged 8 hours at 900F; (b) $[100]_\alpha$ zone in Ti alloy in which Burgers orientation relation between α and β phases exists.

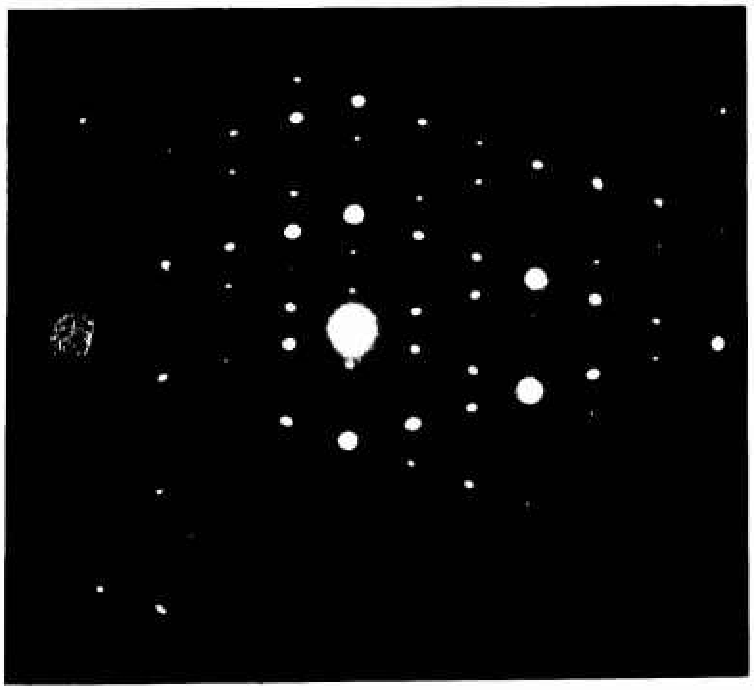


c

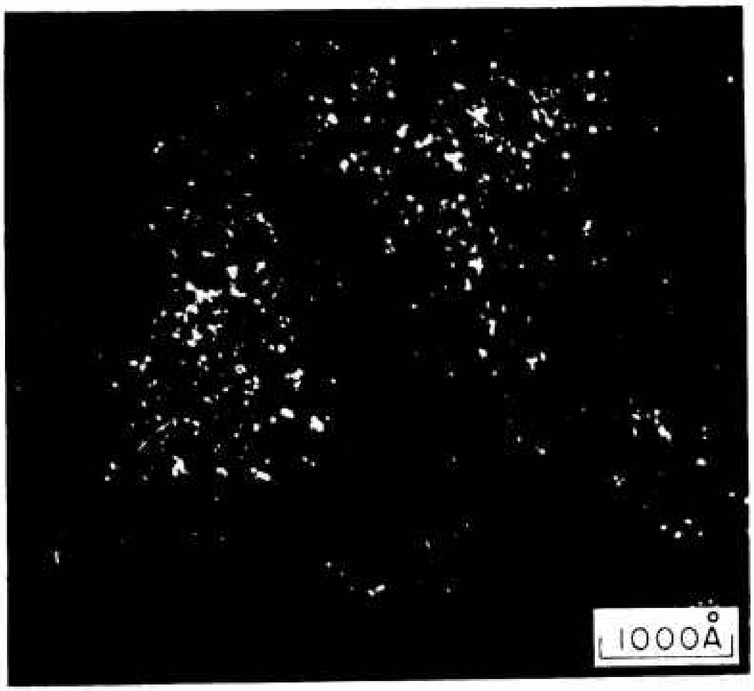


d

Fig. 64 - Selected area diffraction patterns from TEM samples in which α-phase has precipitated in a beta matrix. (c) $[111]_\beta$ zone in Alloy 227 (7Mo-4Cr-2.5Al) solution treated and aged 8 hrs at 900F; and (d) $[111]_\beta$ zone in Ti alloy in which Burgers orientation relation exists.



a



b

Fig. 65 - Athermal omega phase in solution treated Alloy 240 (6Mo-6V) as revealed by TEM. (a) SAD pattern showing superimposed $[113]_\beta$ zone and two $[11\bar{2}0]_\omega$ zones; (b) dark field electron micrograph with $[10\bar{1}1]_\omega$ reflection operating.

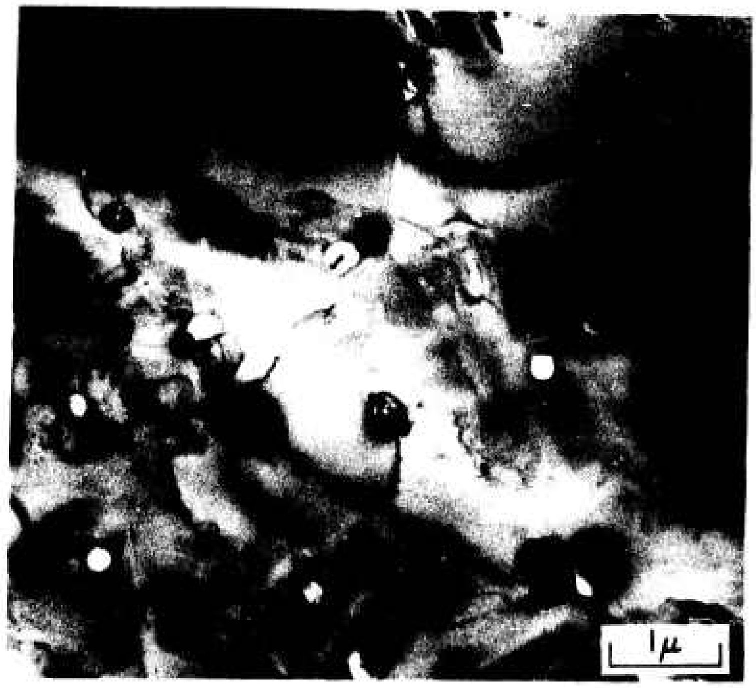


Fig. 66 - Transmission electron micrograph of solution treated Alloy 243 (11Mo-1Al-0.5Si) showing primary α and Ti_5Si_3 particles.

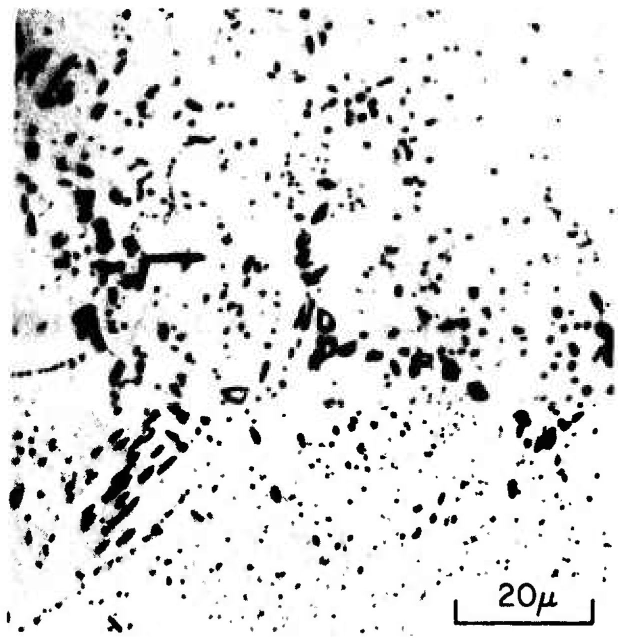


Fig. 67 - Light micrograph of solution treated Alloy 243 (11Mo-1Al-0.5Si) illustrating similarity in size of Ti_5Si_3 and primary α particles.

Fig. 68 - Ellipsoidal omega particles in Alloy 240 (6Mo-6V) solution treated and aged 8 hrs at 800F as revealed by transmission-electron microscopy.

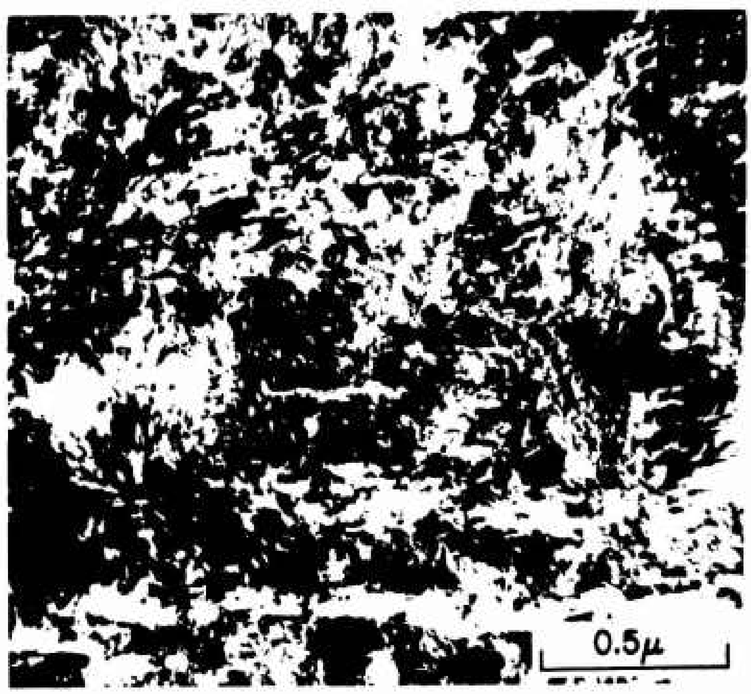


Fig. 69 - Transmission electron micrograph of Alloy 243 (11Mo-1Al-0.5Si) solution treated and aged 8 hrs at 950F showing α-phase precipitation in β matrix.

Fig. 70 Transmission micrograph of Alloy 266 (11Mo-4Al) as solution treated revealing sub-grain structure in β matrix.

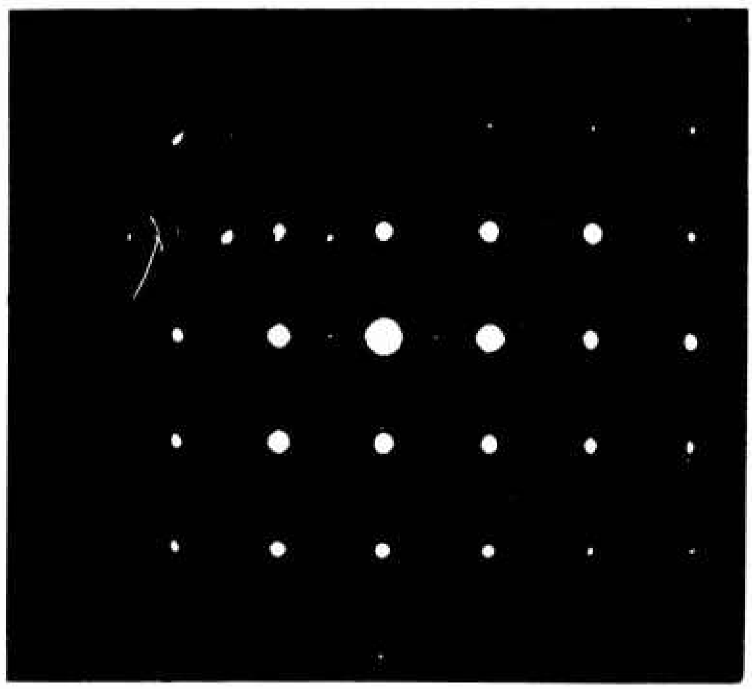
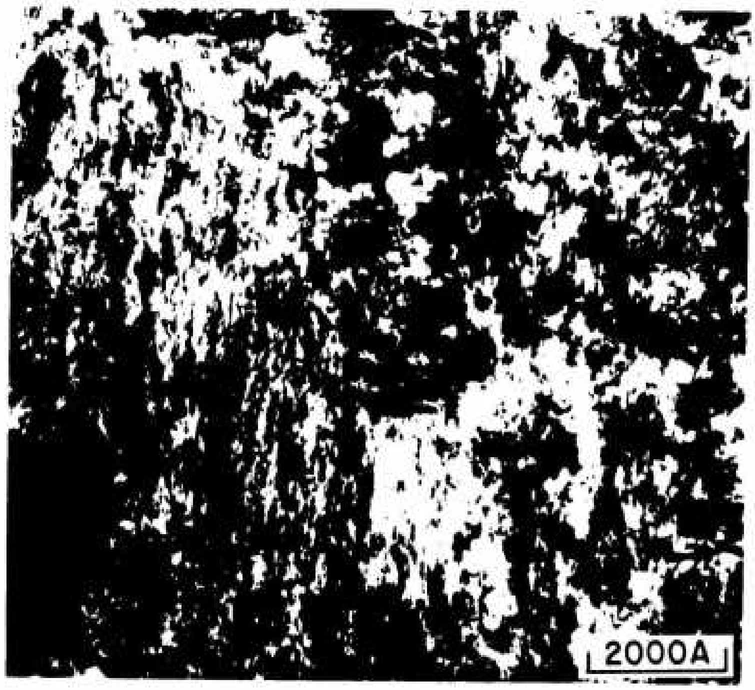
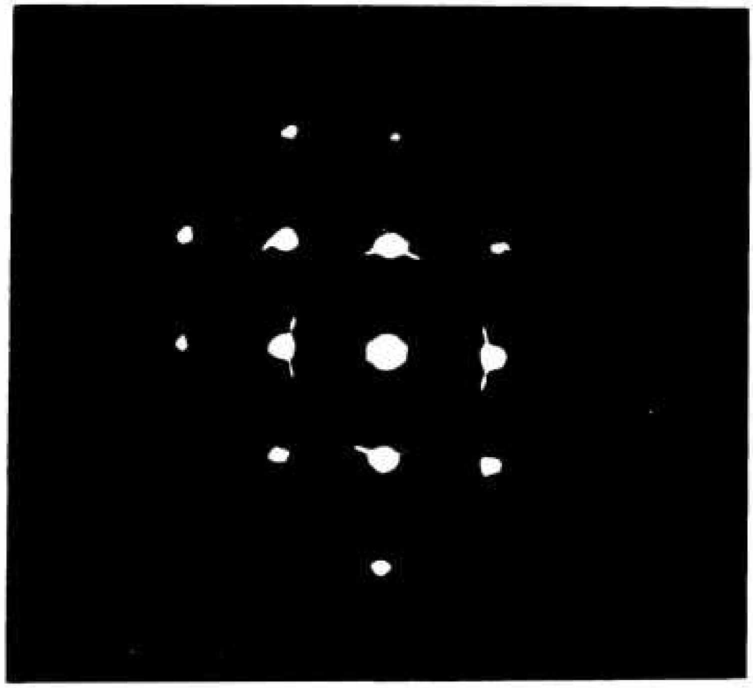


Fig. 71 - Selected area electron diffraction pattern in Alloy 266 indicating grain boundary α-phase precipitate has Burgers orientation relation with β matrix.



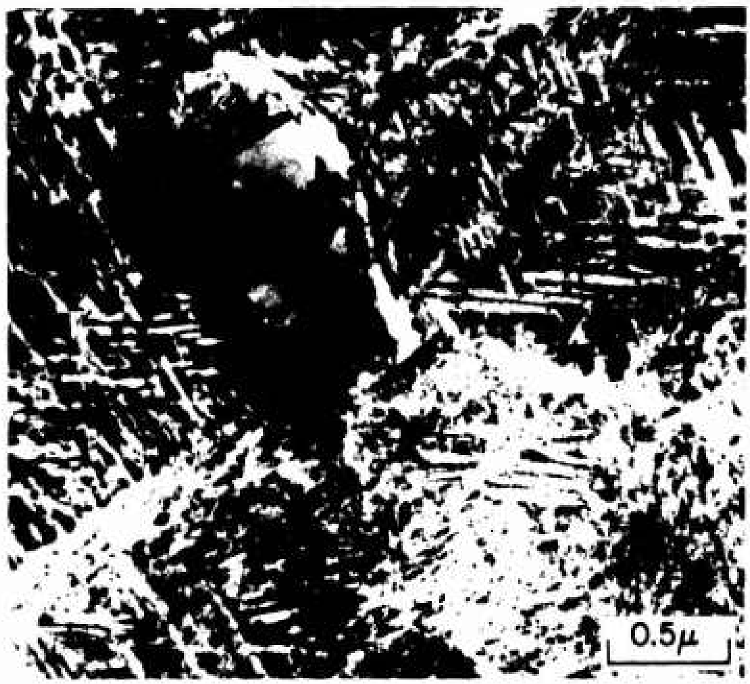
a



b

Fig. 72 Alloy 266 (11Mo-4Al) solution treated and aged 2 minutes at 1000F. (a) Transmission electron micrograph revealing high density of α precipitates; (b) selected area electron diffraction pattern indicating α-precipitates do not have Burgers orientation relation with β matrix.

a



b

Fig. 73 - Transmission electron micrographs of Alloy 266 (11Mo-4Al) solution treated and aged at 1000F illustrating agglomeration of α-phase precipitates. (a) 8 hour age, dark field micrograph with $(10\bar{1}0)_\alpha$ reflection operating, and (b) 48 hour age, bright field micrograph.

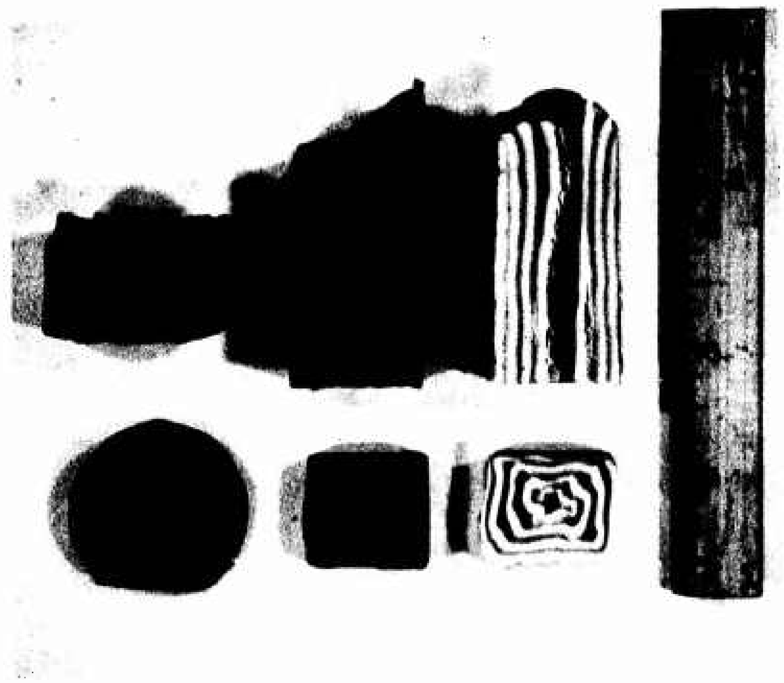


Figure 74. Simulation of Phase III forging using plasticine "swiss-rolls". (Left) "Swiss-roll" compiled from two different colored strands of plasticine. (Middle) "Swiss-roll" after simulated tri-directional forging sequence (Figure 75). (Right) "Swiss-roll" after simulated uni-directional forging sequence. Longitudinal cross-section is shown at the top and transverse cross-section at the bottom in each case. Note increased distortion of plasticine in the center of the "Swiss-roll" after tri-directional working.

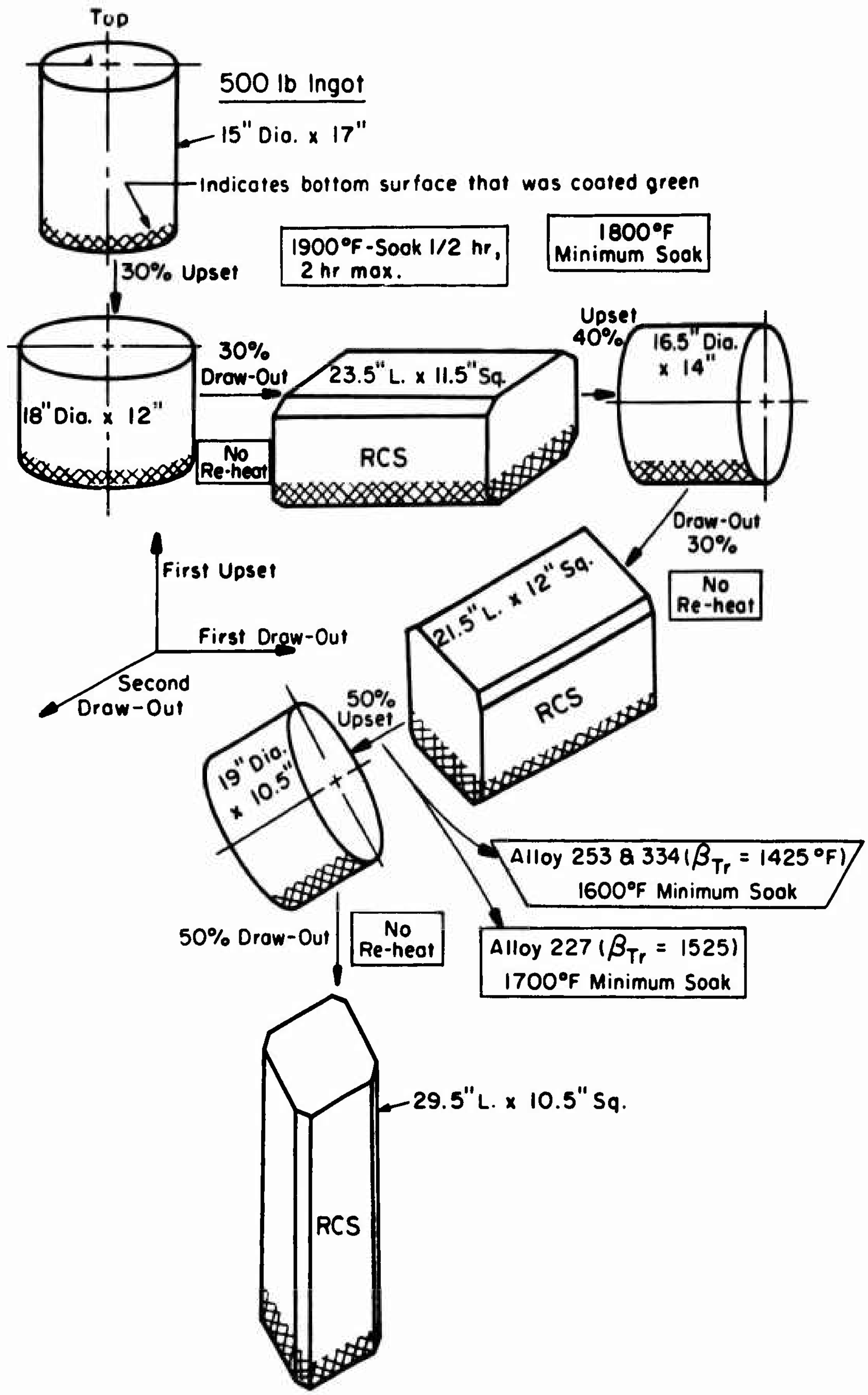


Figure 75. Tri-directional (three directions mutually at right angles) primary forging sequence used to convert ingots to 10.5 inch RCS bloom.

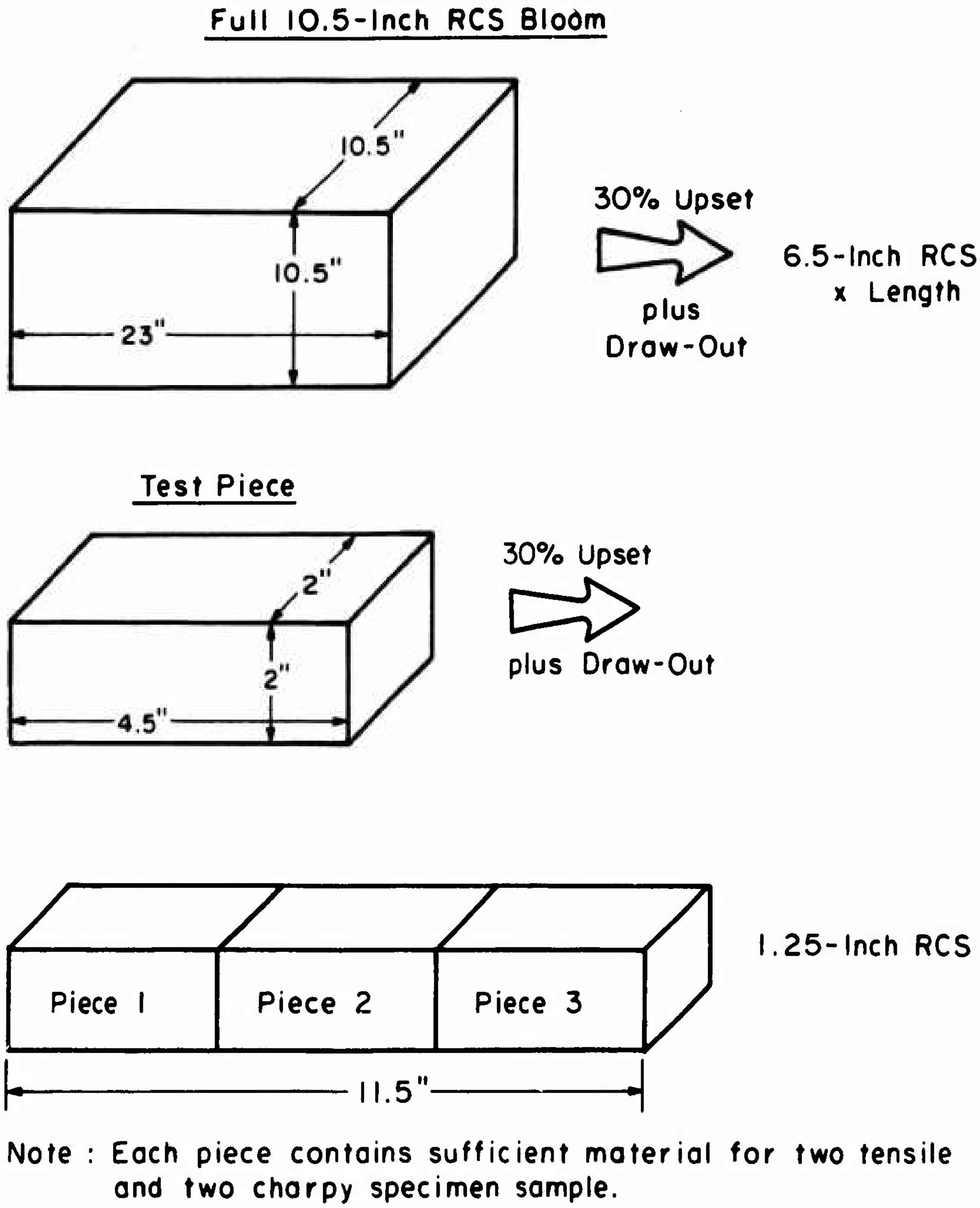


Figure 76. Schematic illustration of conversion of full sized 10.5 mil RCS bloom to 6 inch diameter billet and corresponding samples used to simulate this processing sequence.

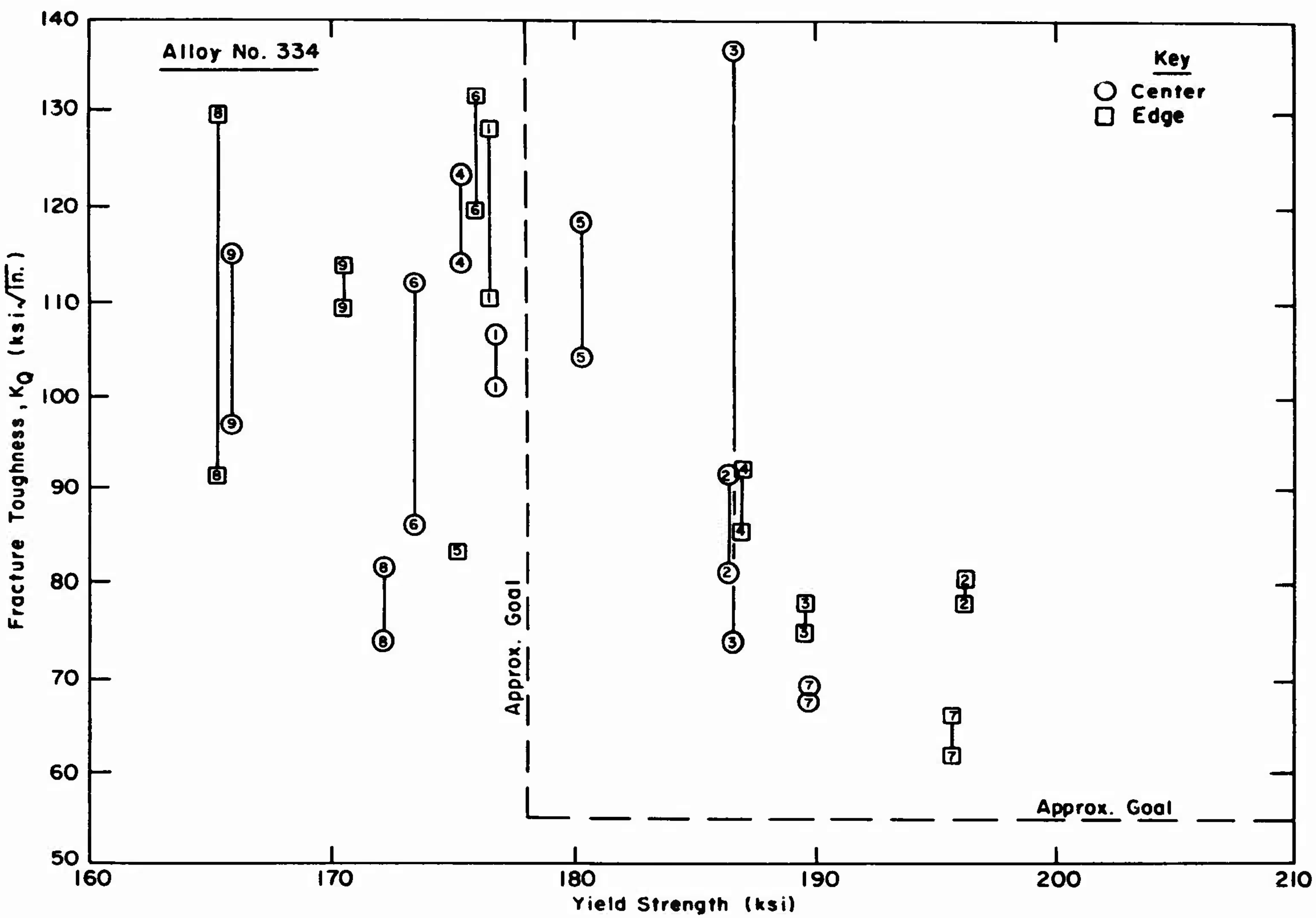


Figure 77. Alloy 334 (10Mo-6Cr-2.5Al). Comparison of yield strength - toughness after the various TMT sequences defined in Tables XXXVIII and XLII. Treatments corresponding to the various codes are defined in the referenced Tables.

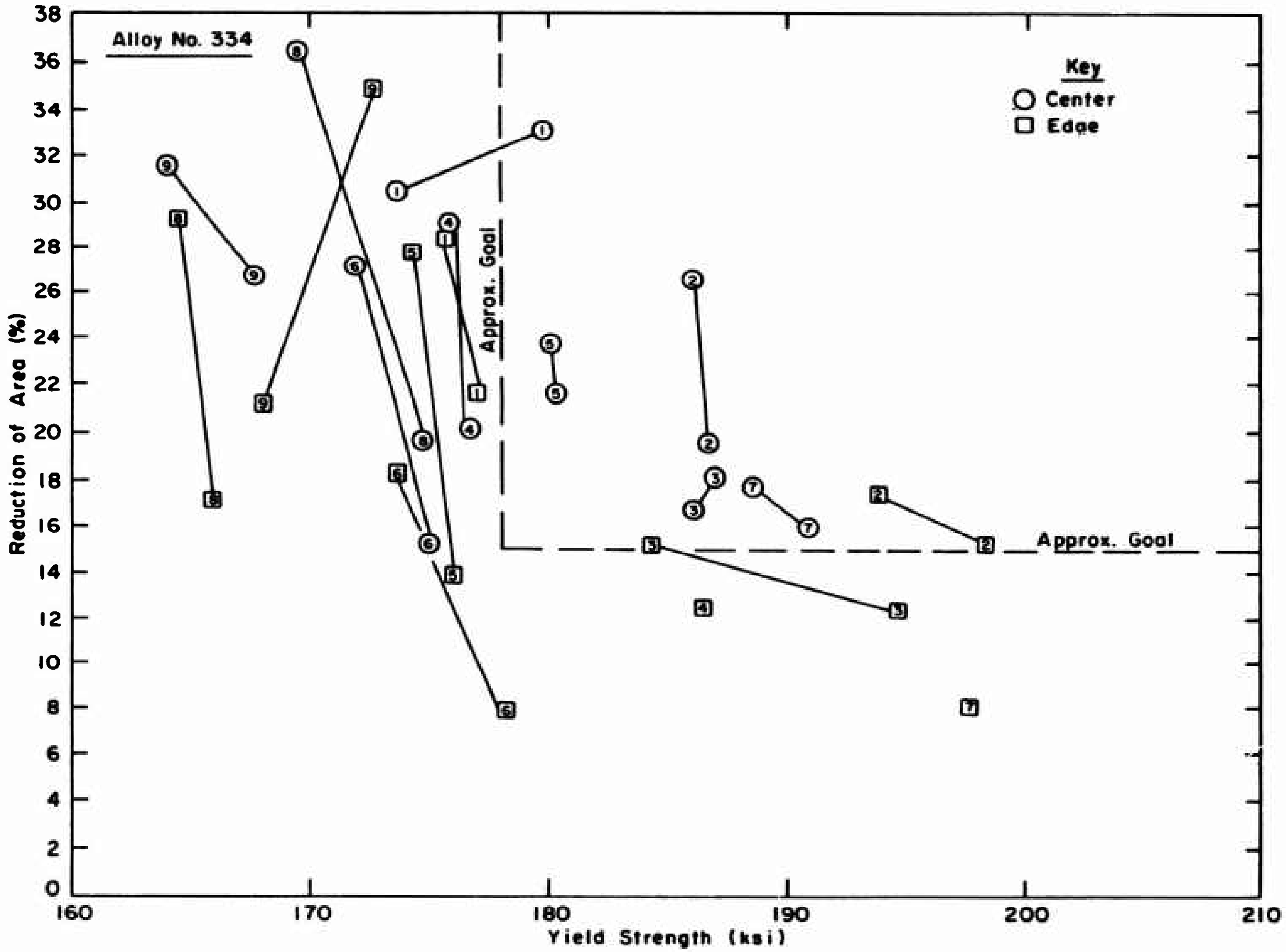


Figure 78. Alloy 334 (10Mo-6Cr-2.5Al). Comparison of yield strength - reduction of area after the various TMT sequences defined in Tables XXXVIII and XLII. Treatments corresponding to the various codes are defined in the referenced Tables.

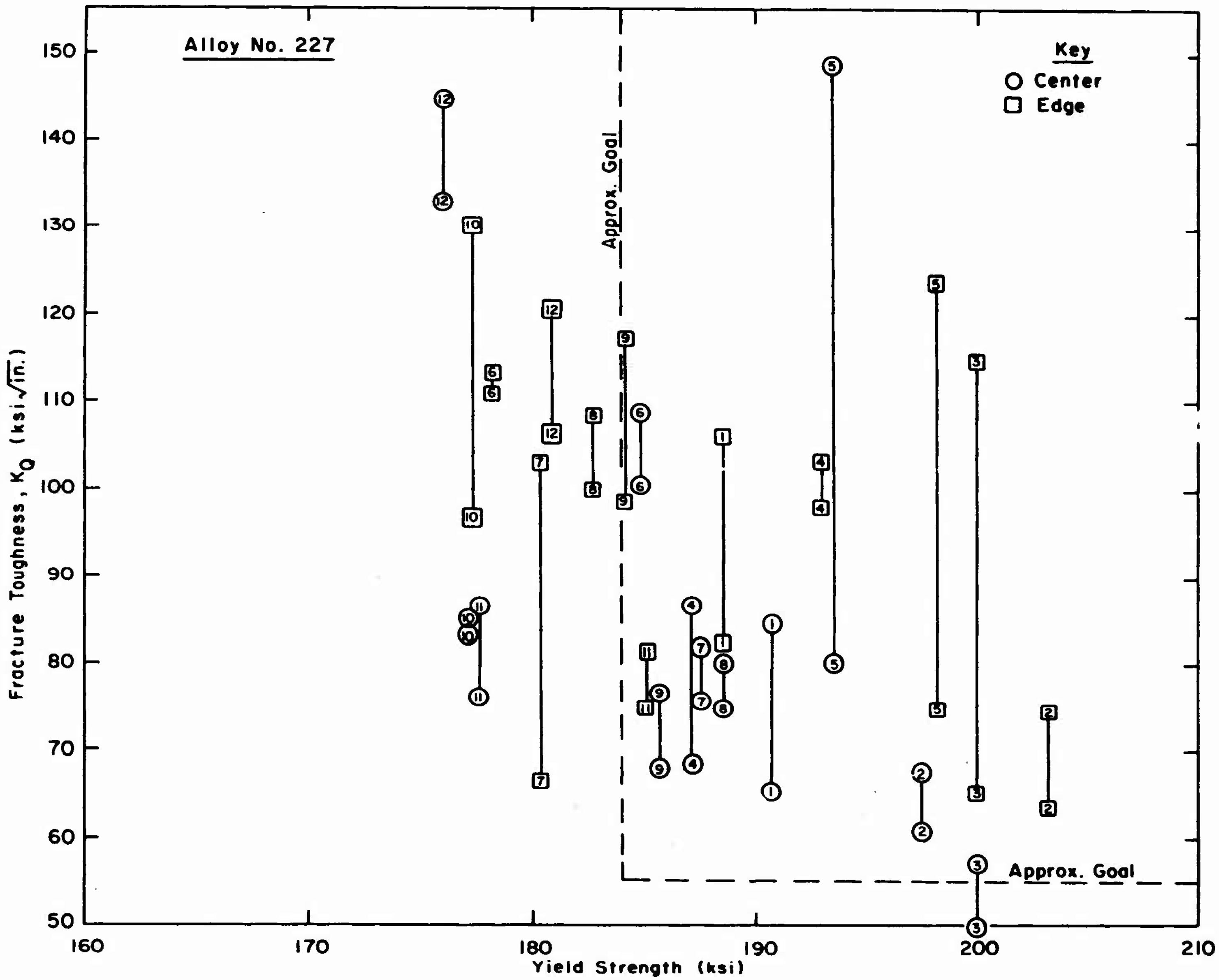


Figure 79. Alloy 227 (7Mo-4Cr-25Al). Comparison of yield strength - toughness after the various TMT sequences defined in Tables XXXIX and XLIV. Treatments corresponding to the various codes are defined in the referenced Tables.

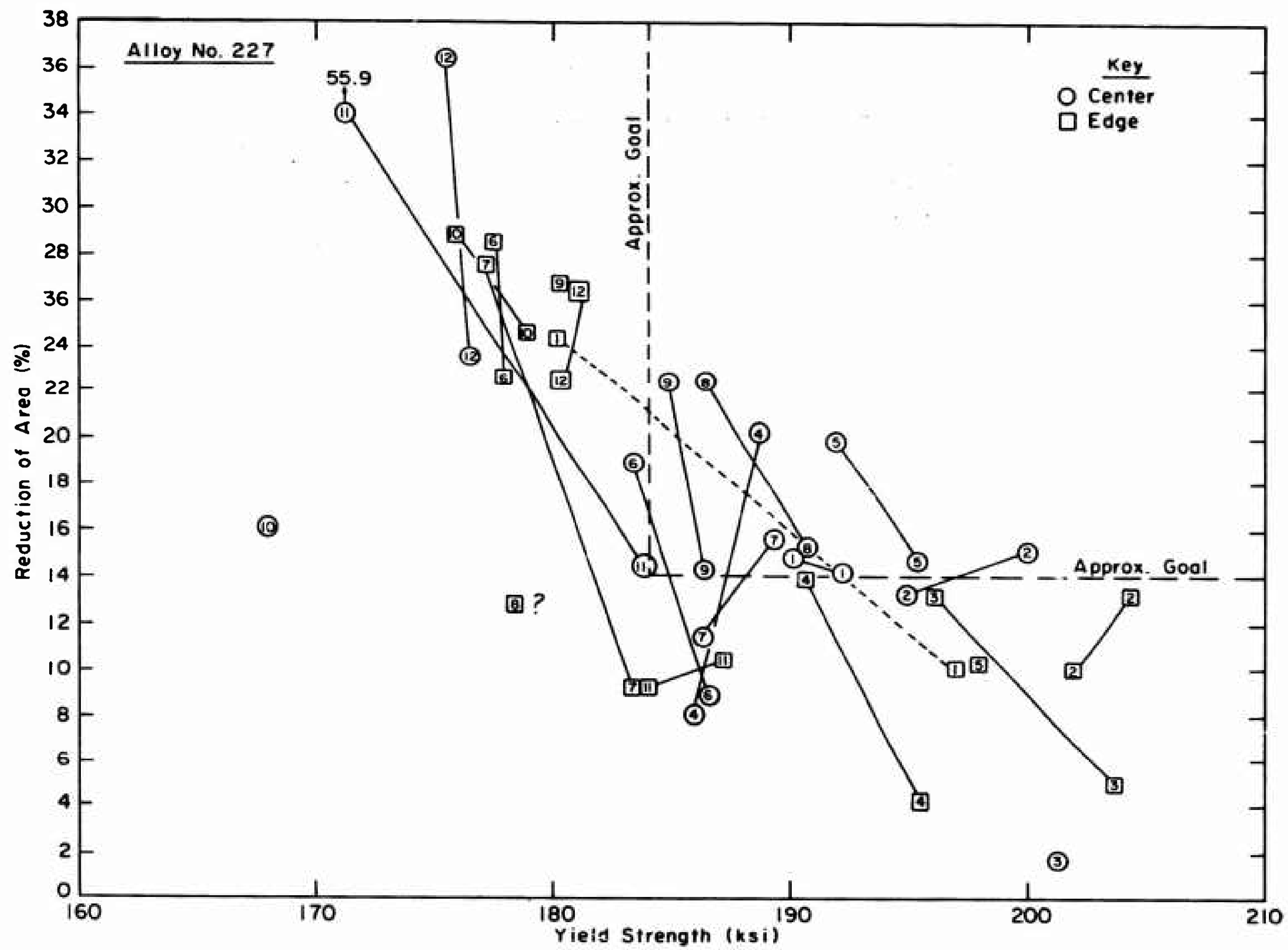


Figure 80. Alloy 227 (7Mo-4Cr-2.5Al). Comparison of yield strength - reduction of area after the various TMT sequences defined in Tables XXXIX and XLIV. Treatments corresponding to the various codes are defined in the referenced Tables.

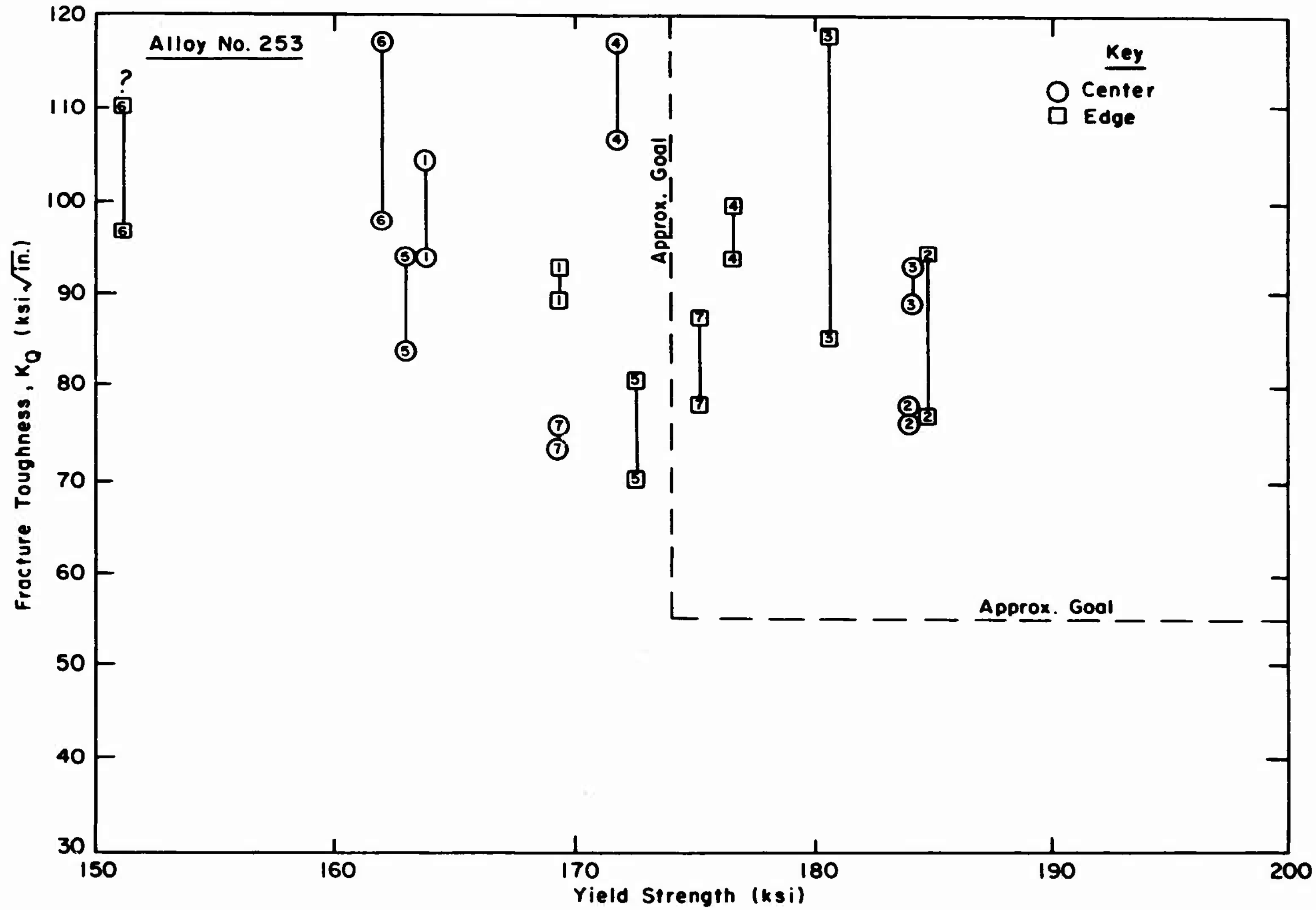


Figure 81. Alloy 253 (10Mo-8V-2.5Al). Comparison of yield strength - toughness after the various TMT sequences defined in Tables XL and XLIII. Treatments corresponding to the various codes are defined in the referenced Tables.

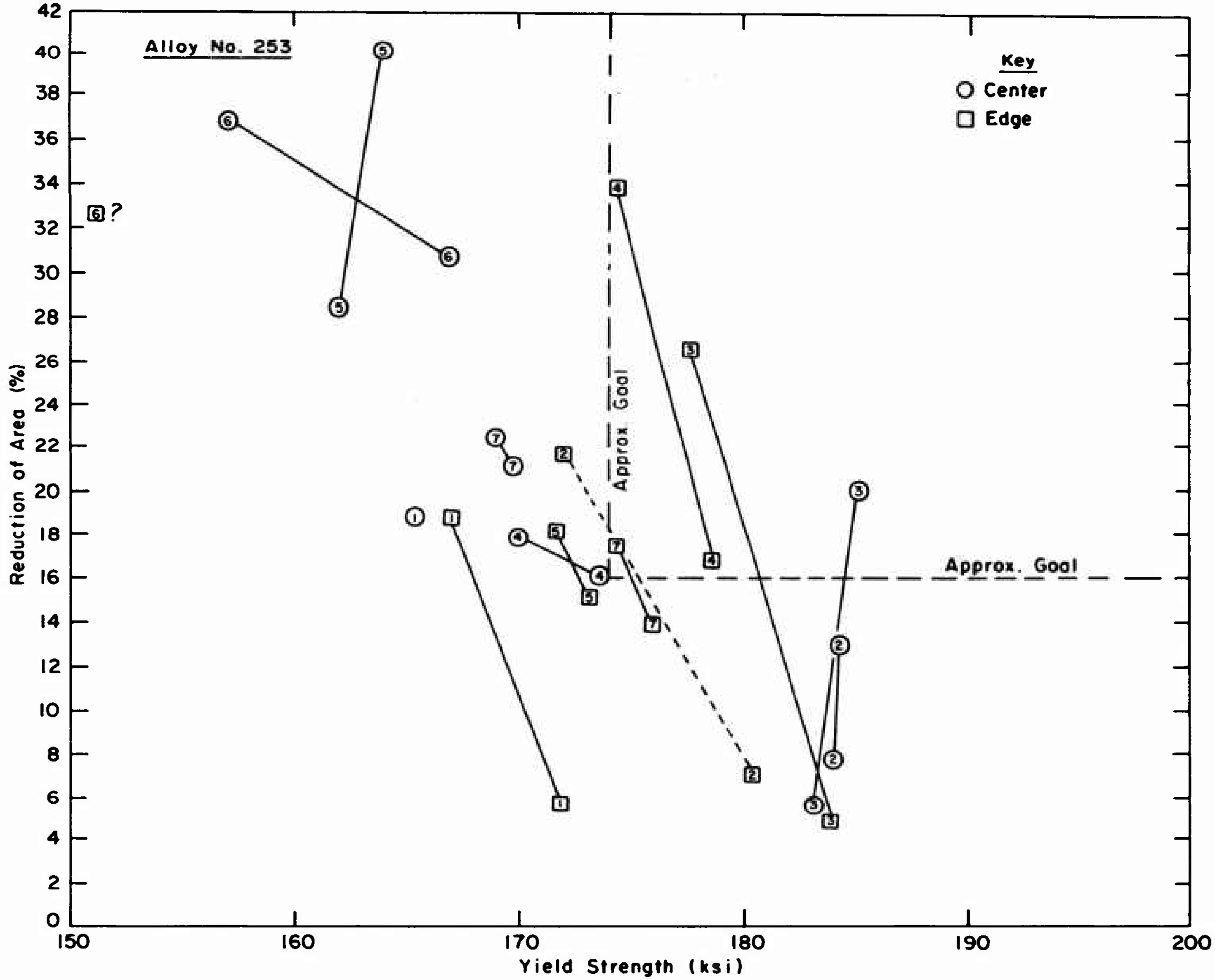


Figure 82. Alloy 253 (10Mo-8V-2.5Al). Comparison of yield strength - reduction of area after the various TMT sequences defined in Tables XL and XLIII. Treatments corresponding to the various codes are defined in the referenced Tables.

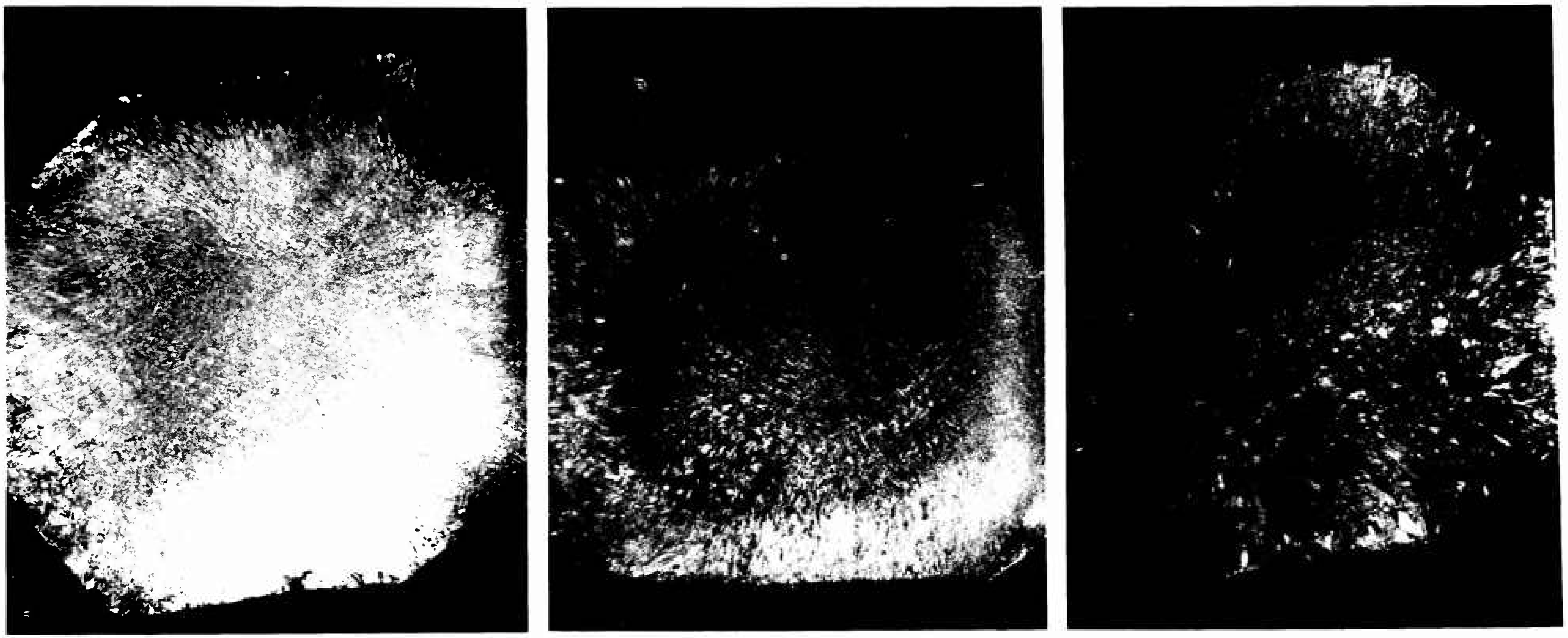


Figure 83. Photomacrographs at 6-3/4 inch RCS billet stage. (Left) Alloy 334 (10Mo-6Cr-2.5Al), (Center) Alloy 227 (7Mo-4Cr-2.5Al) and, (Right) Alloy 253 (10Mo-8V-2.5 Al). Detailed study of microstructure revealed no evidence of "beta flecks." Approximate magnification X1/2.

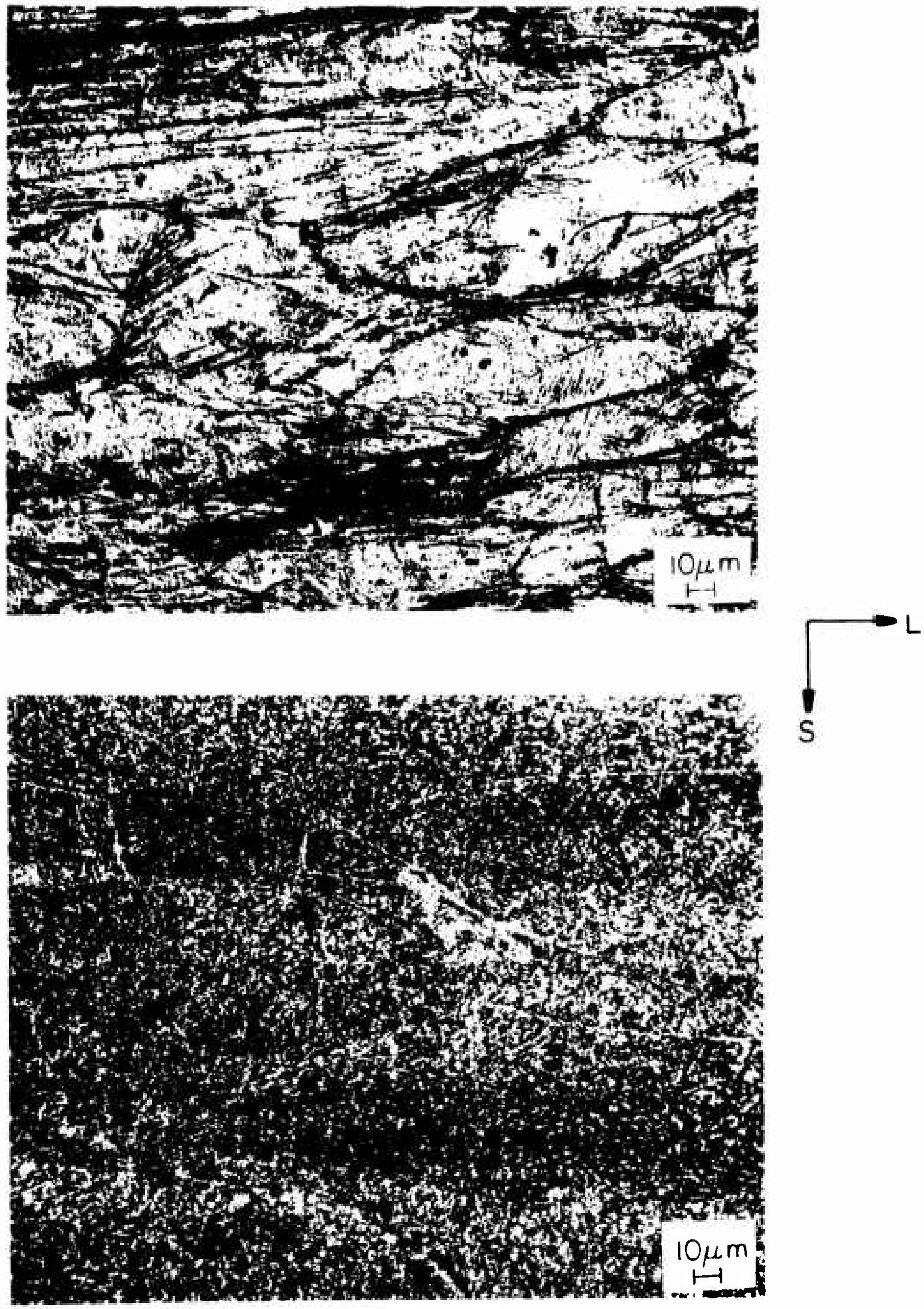


Figure 84. Microstructure of (top) Alloy 334 (10Mo-6Cr-2.5Al) and (bottom) Alloy 227 (7Mo-4Cr-2.5Al) as forged from 10.5 inch RCS to 6-3/4 inch RCS and allowed to air cool, both X275.

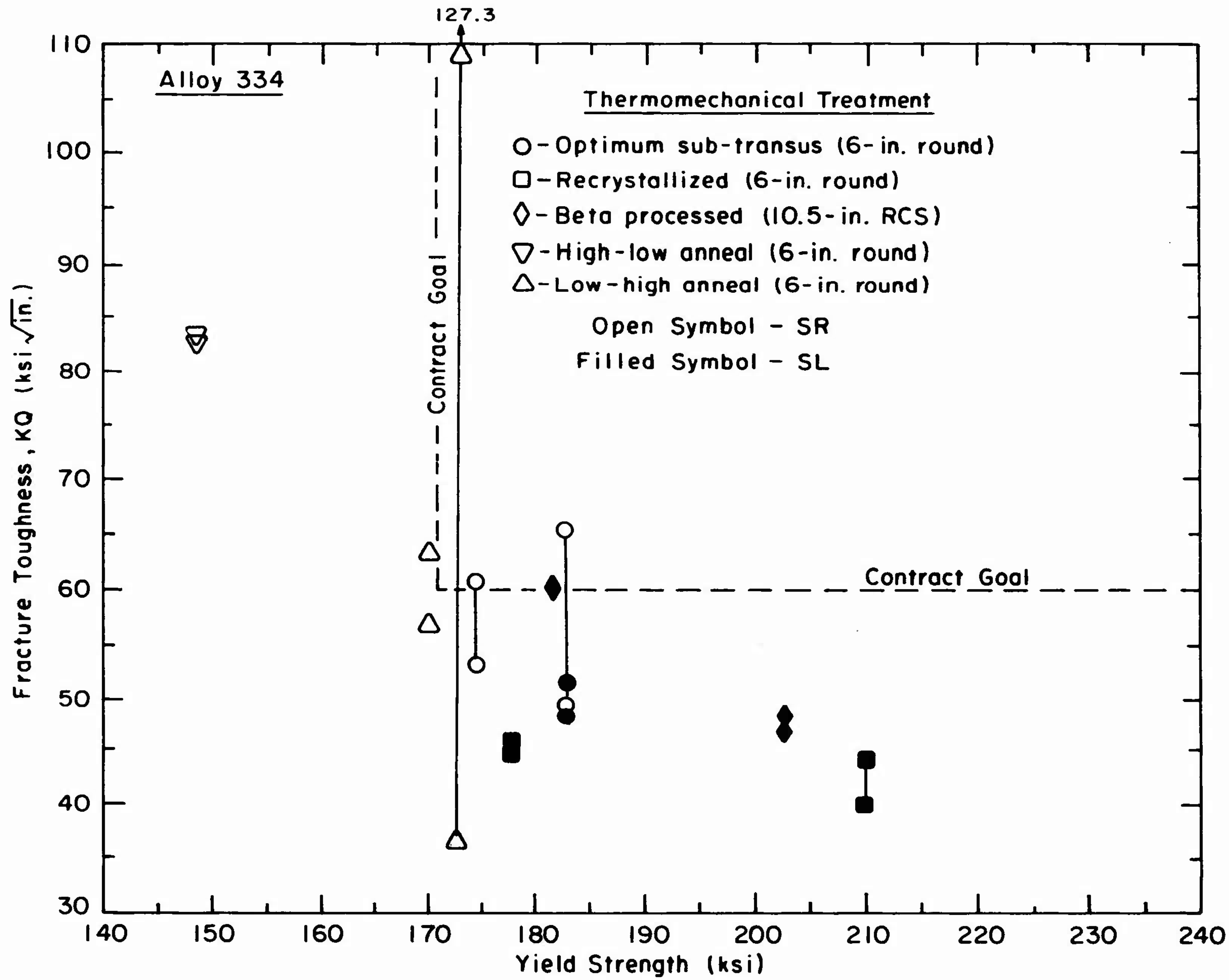


Figure 85. Transverse yield strength - toughness (K_Q) alloy 334 (10Mo-6Cr-2.5Al) after various thermomechanical treatments.

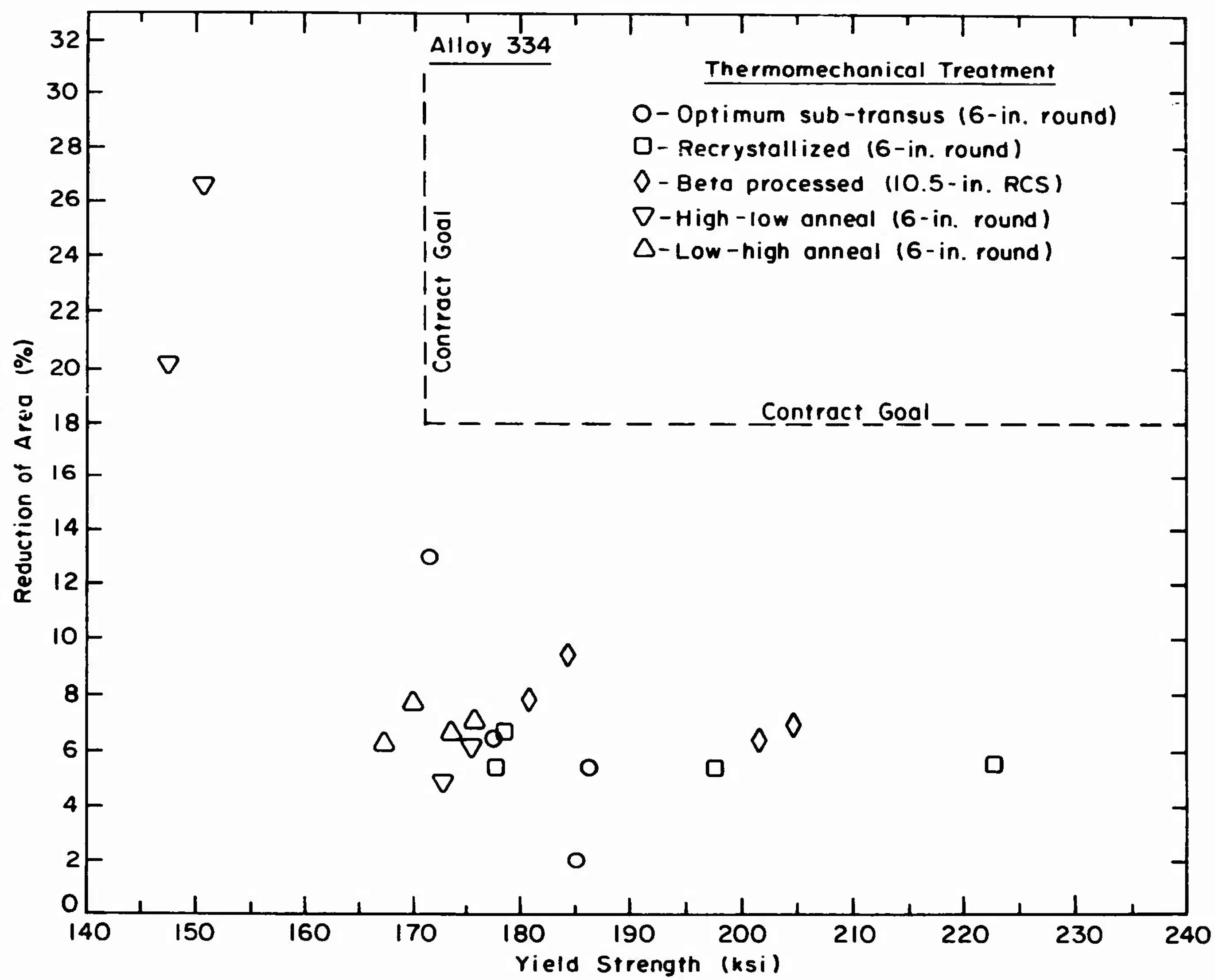


Figure 86. Transverse yield strength - ductility (RA) alloy 334 (10Mo-6Cr-2.5Al) after various thermomechanical treatments.

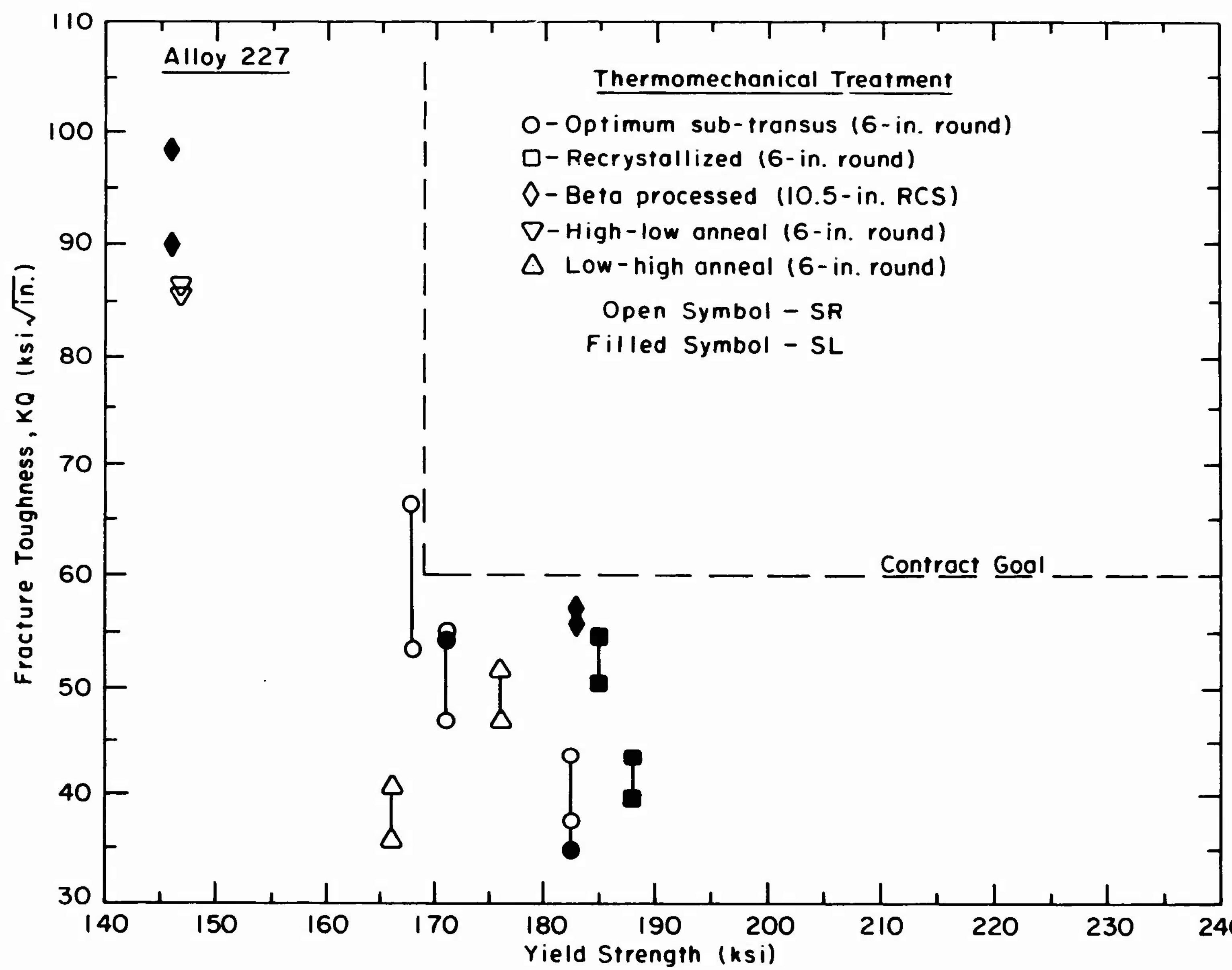


Figure 87. Transverse yield strength - toughness (K_Q) alloy 227 (7Mo-4Cr-2.5Al) after various thermomechanical treatments.

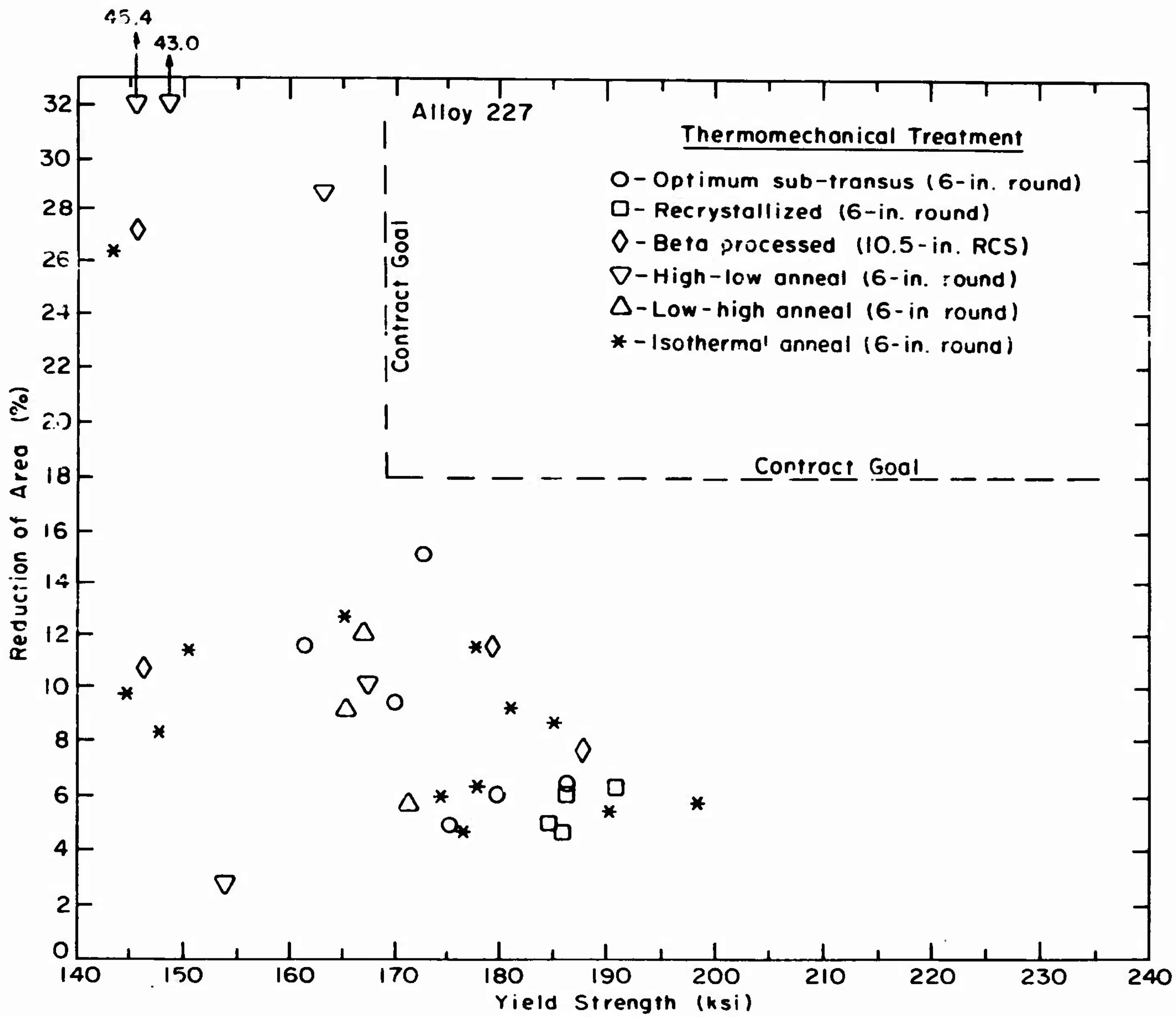


Figure 88. Transverse yield strength - ductility (RA) alloy 227 (7Mo-4Cr-2.5Al) after various thermomechanical treatments.

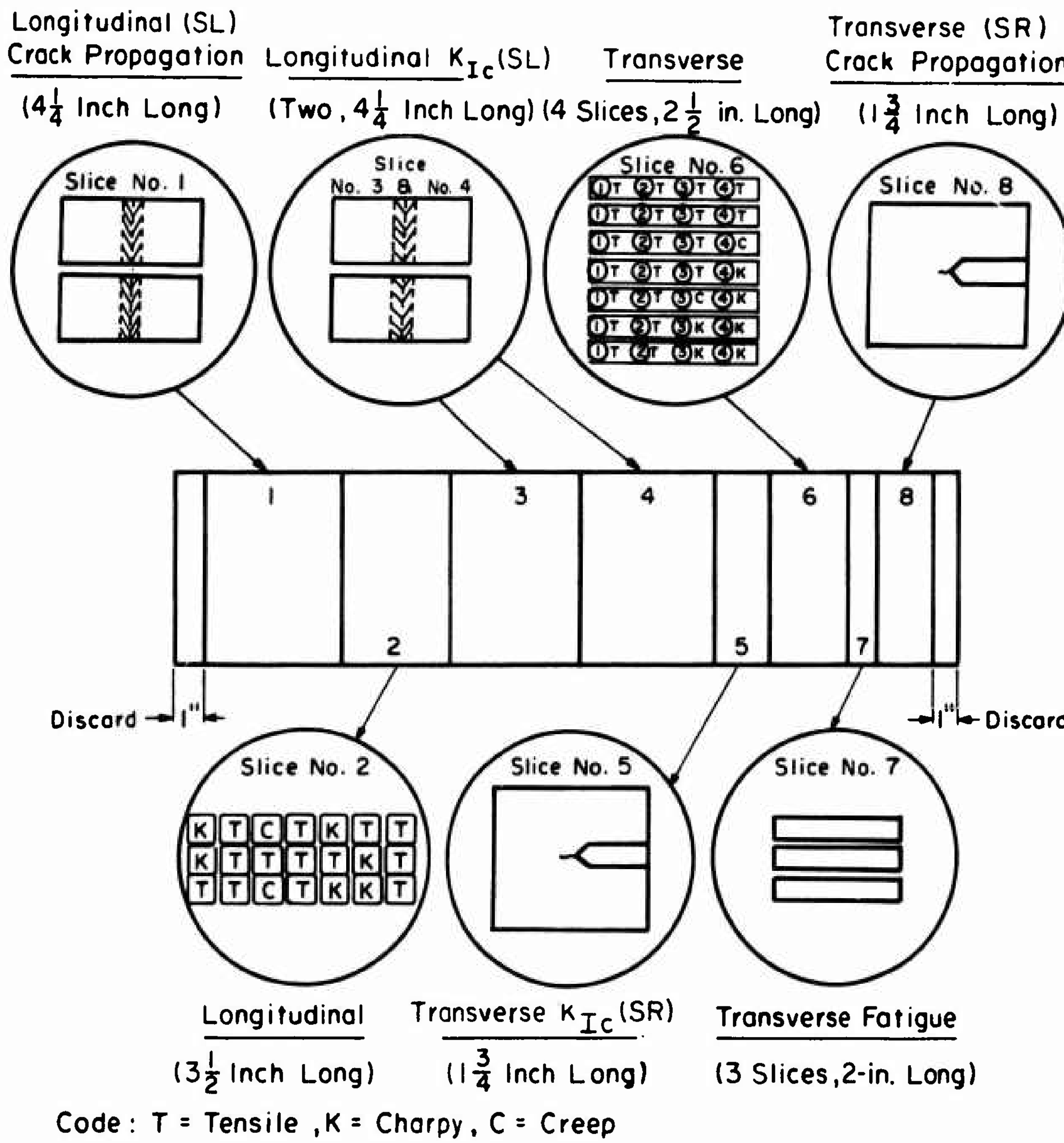


Figure 89. Specimen location diagram, indicating position of the various types of samples in the full six inch diameter billet.

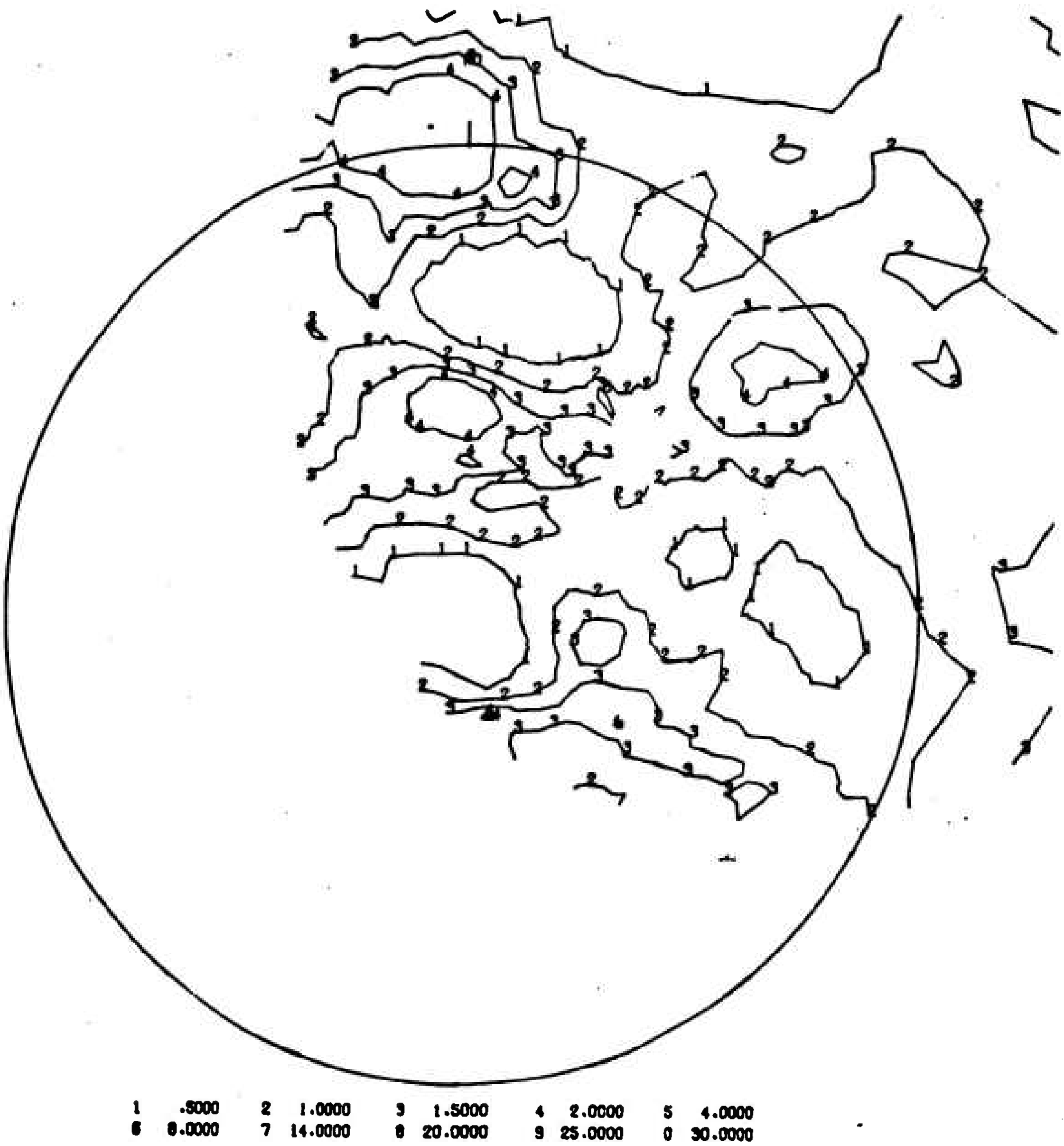


Figure 90a. Pole figure of alloy 334 (10Mo-6Cr-2.5Al) plate, (110) beta planes. RW plane with R orientated top to bottom of page (see Appendices D and F).

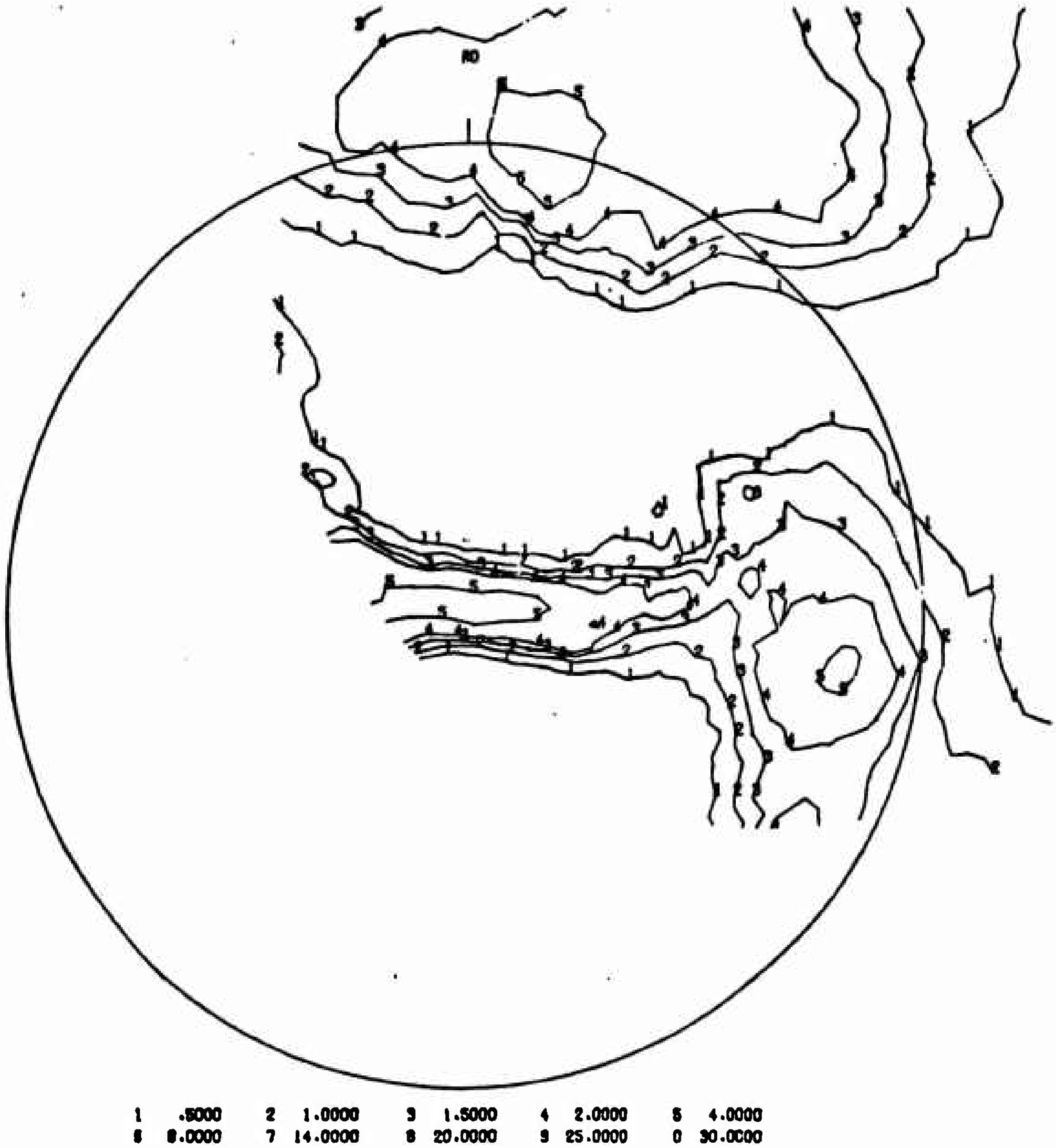


Figure 90b. Pole figure of alloy 334 (10Mo-6Cr-2.5Al) plate, (200) beta planes. RW plane with R orientated top to bottom of page (see Appendices D and F).

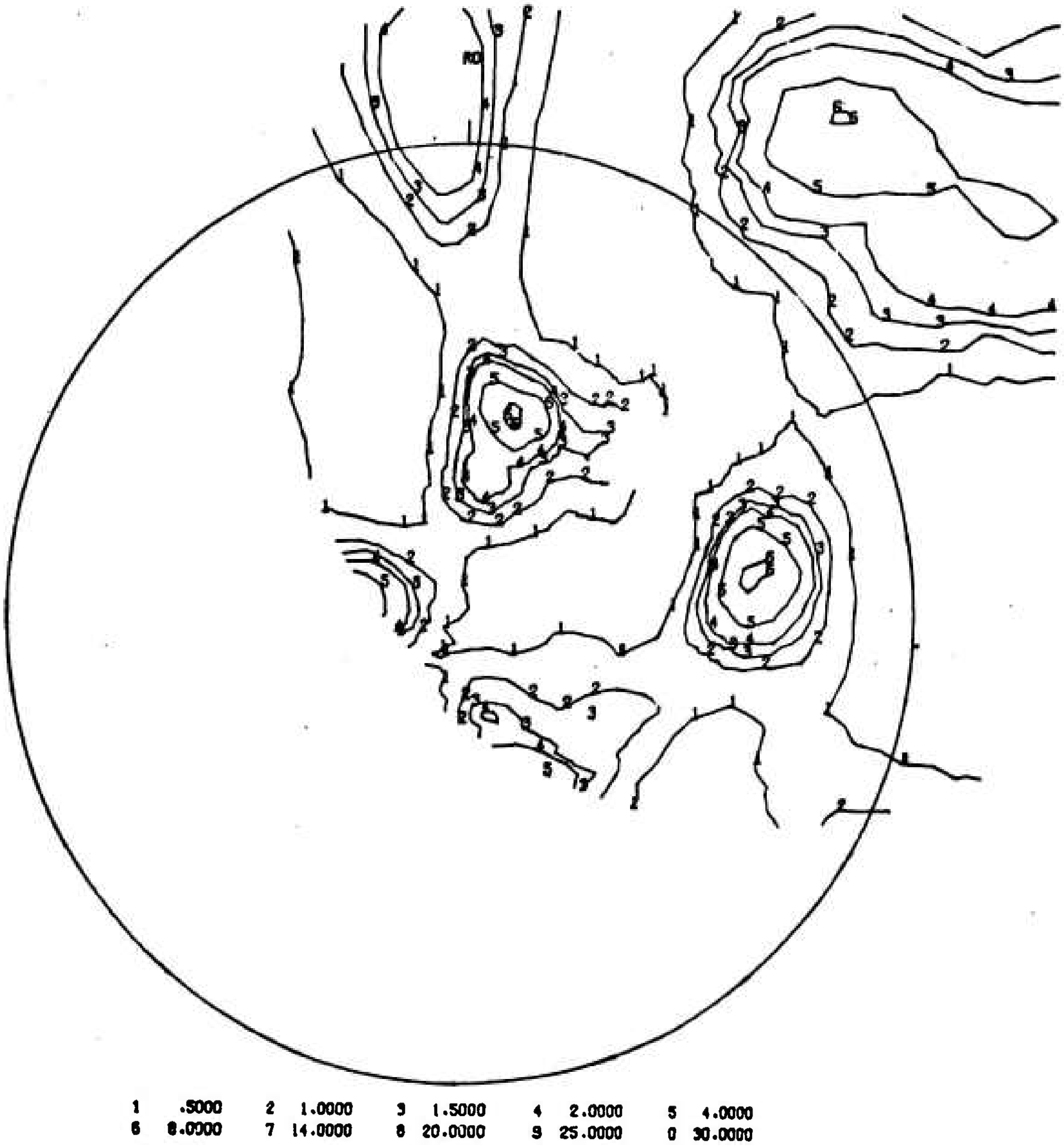


Figure 91a. Pole figure of alloy 334 (10Mo-6Cr-2.5Al) billet, (110) beta planes. SR plane (See Appendices D and F)

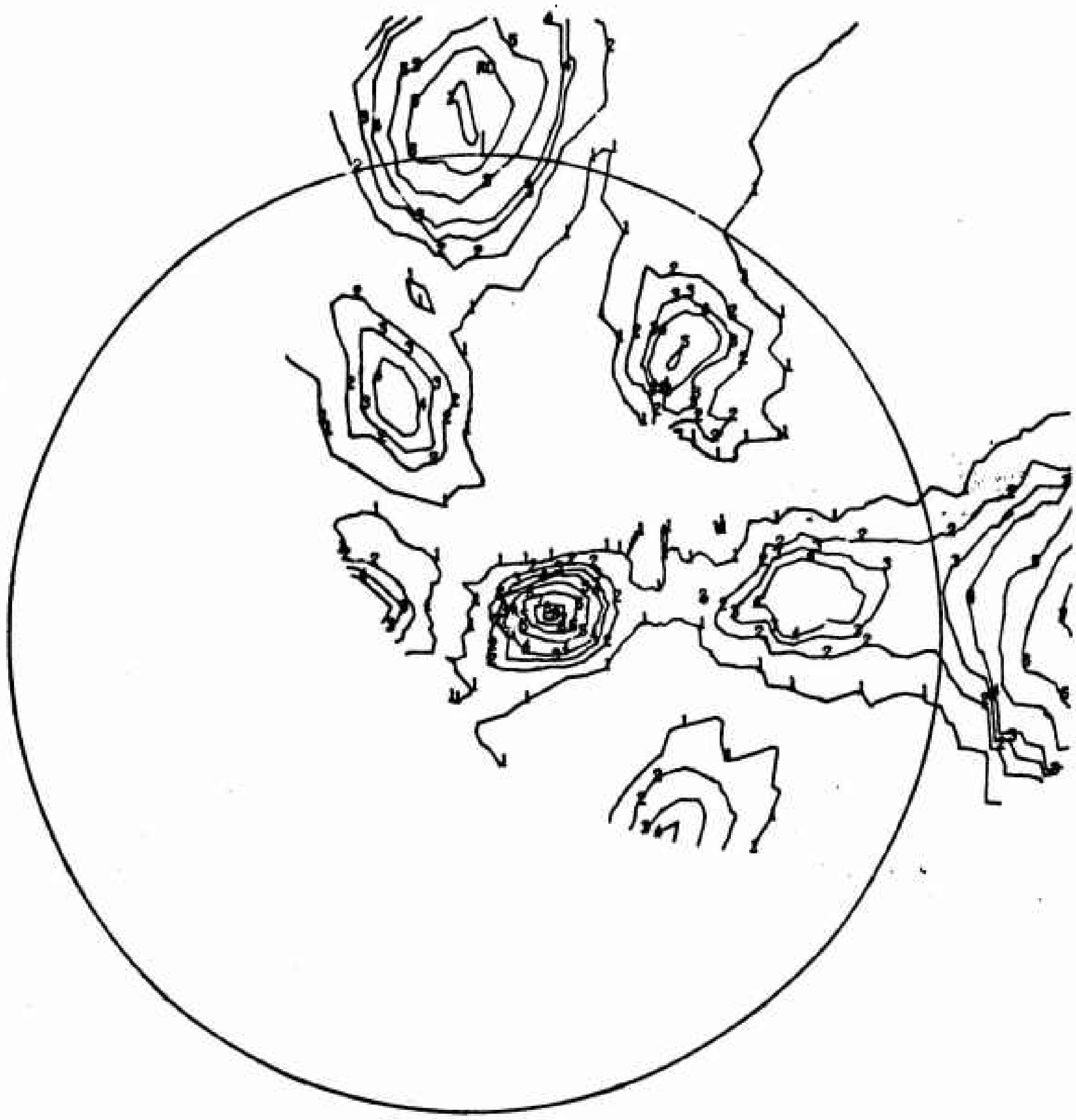


Figure 91b. Pole figure of alloy 334 (10Mo-6Cr-2.5Al) billet, (200) beta planes. SR plane (See Appendices D and F).

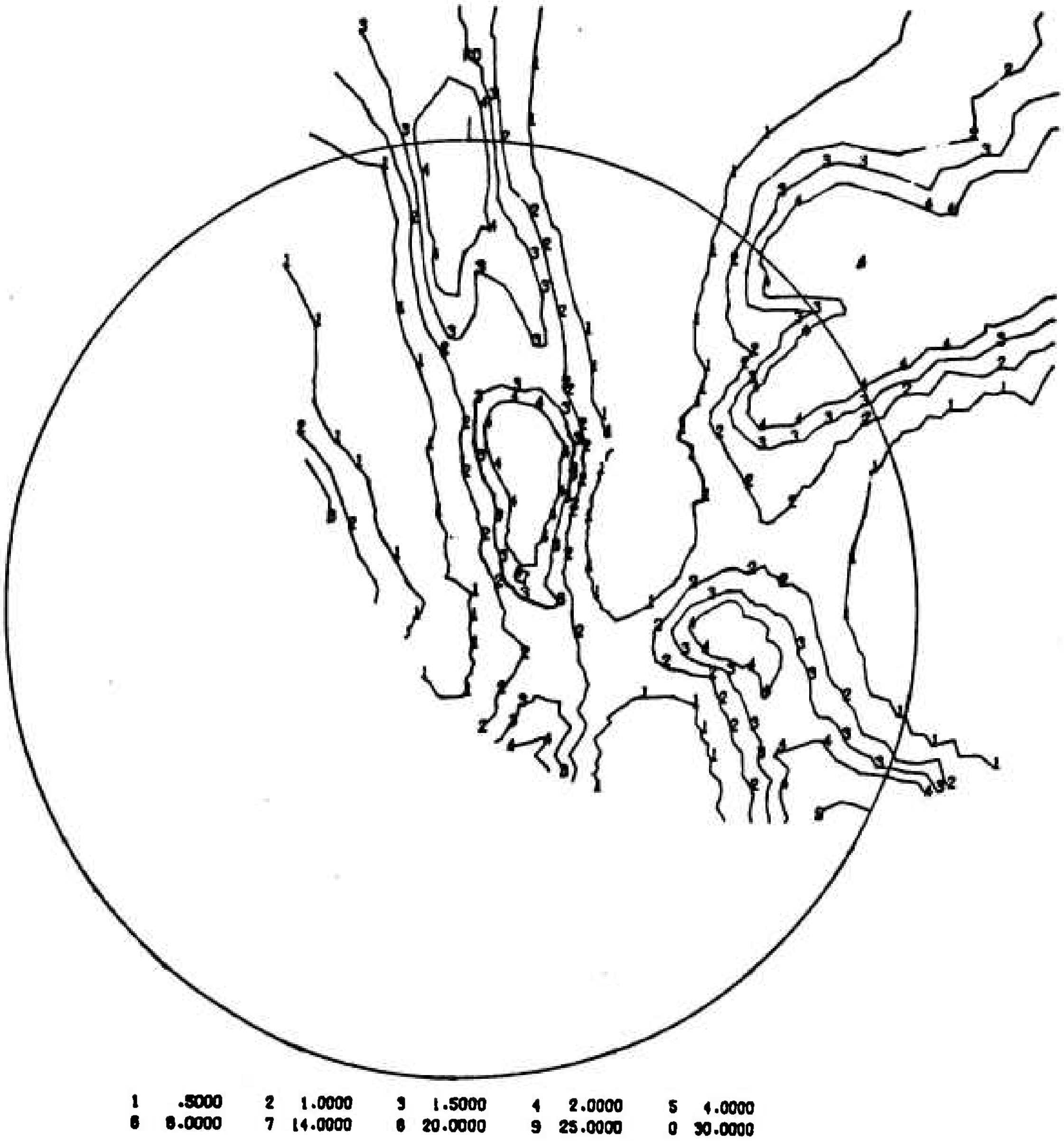


Figure 92a. Pole figure of alloy 227 (7Mo-4Cr-2.5Al) billet, (110) beta planes. SR plane (see Appendices D and F).

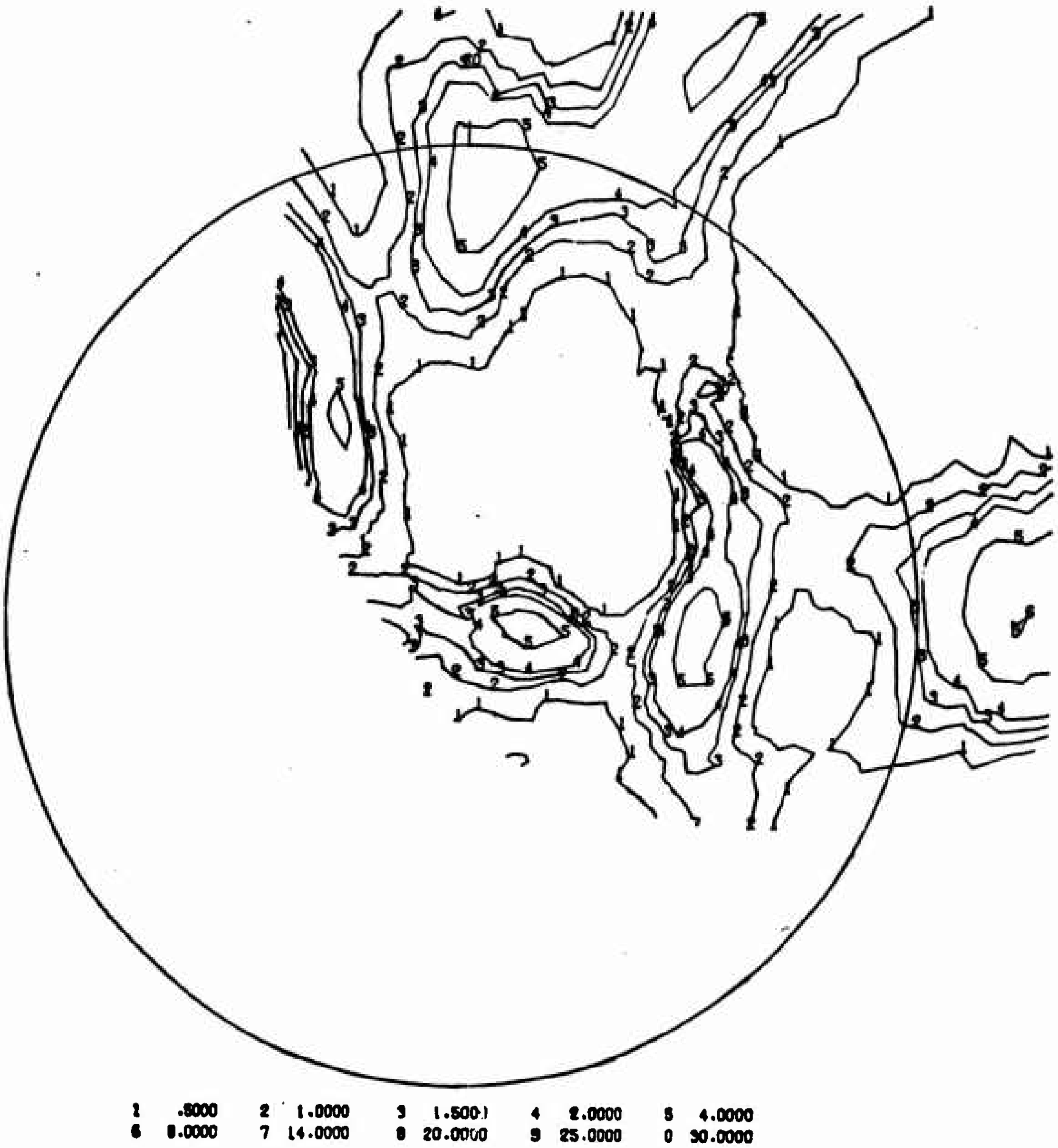


Figure 92b. Pole figure of alloy 227 (7Mo-4Cr-2.5Al) billet, (200) beta planes. SR plane (see Appendices D and F).

Figure 93a. Pole figure of alloy 334 (10Mo-6Cr-2.5Al) billet, (110) beta planes, LS plane with L orientated top to bottom of page (see Appendices D and F).

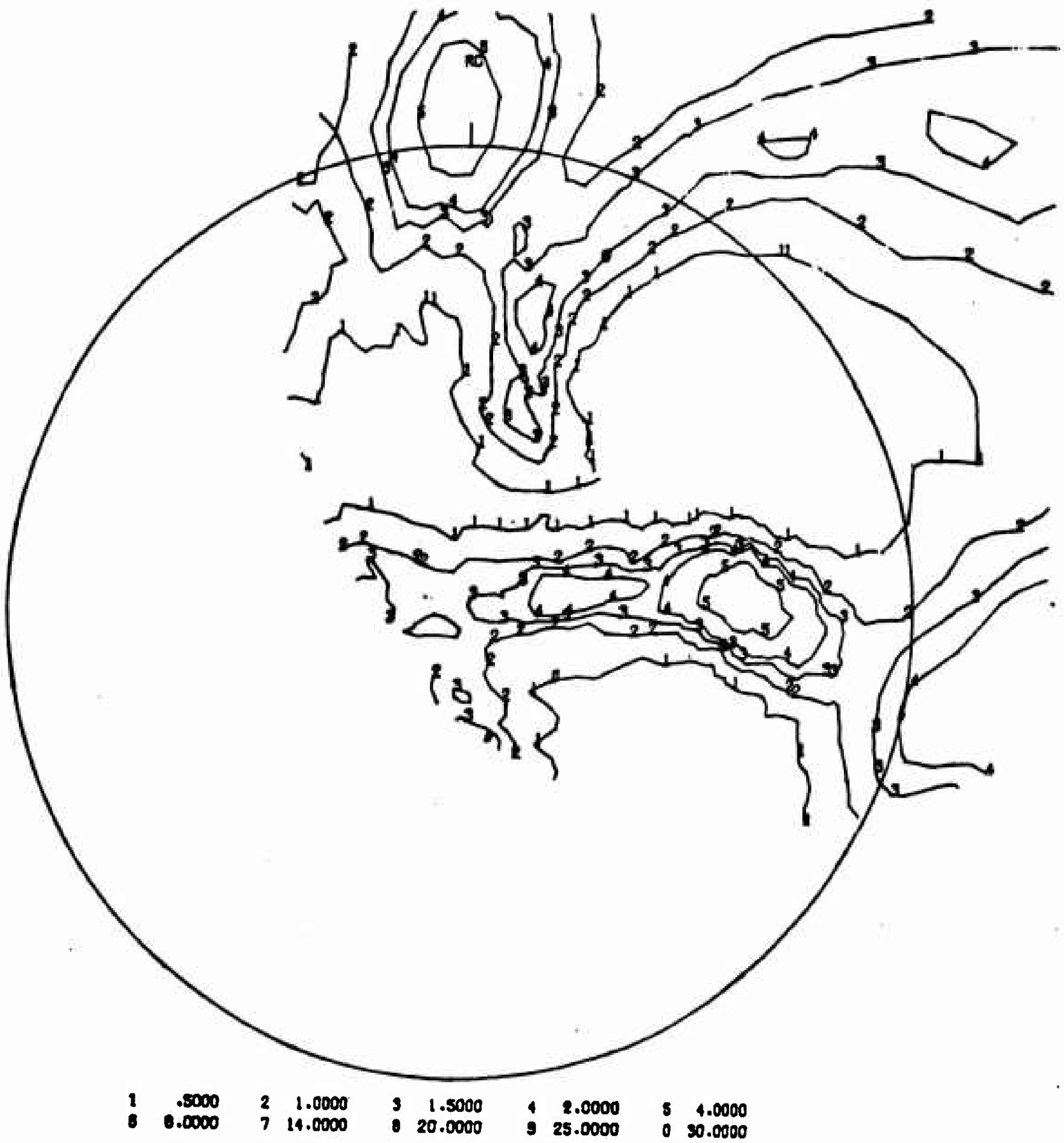


Figure 93b. Pole figure of alloy 334 (10Mo-6Cr-2.5Al) billet, (200) beta planes, LS plane with L orientated top to bottom of page (see Appendices D and F).

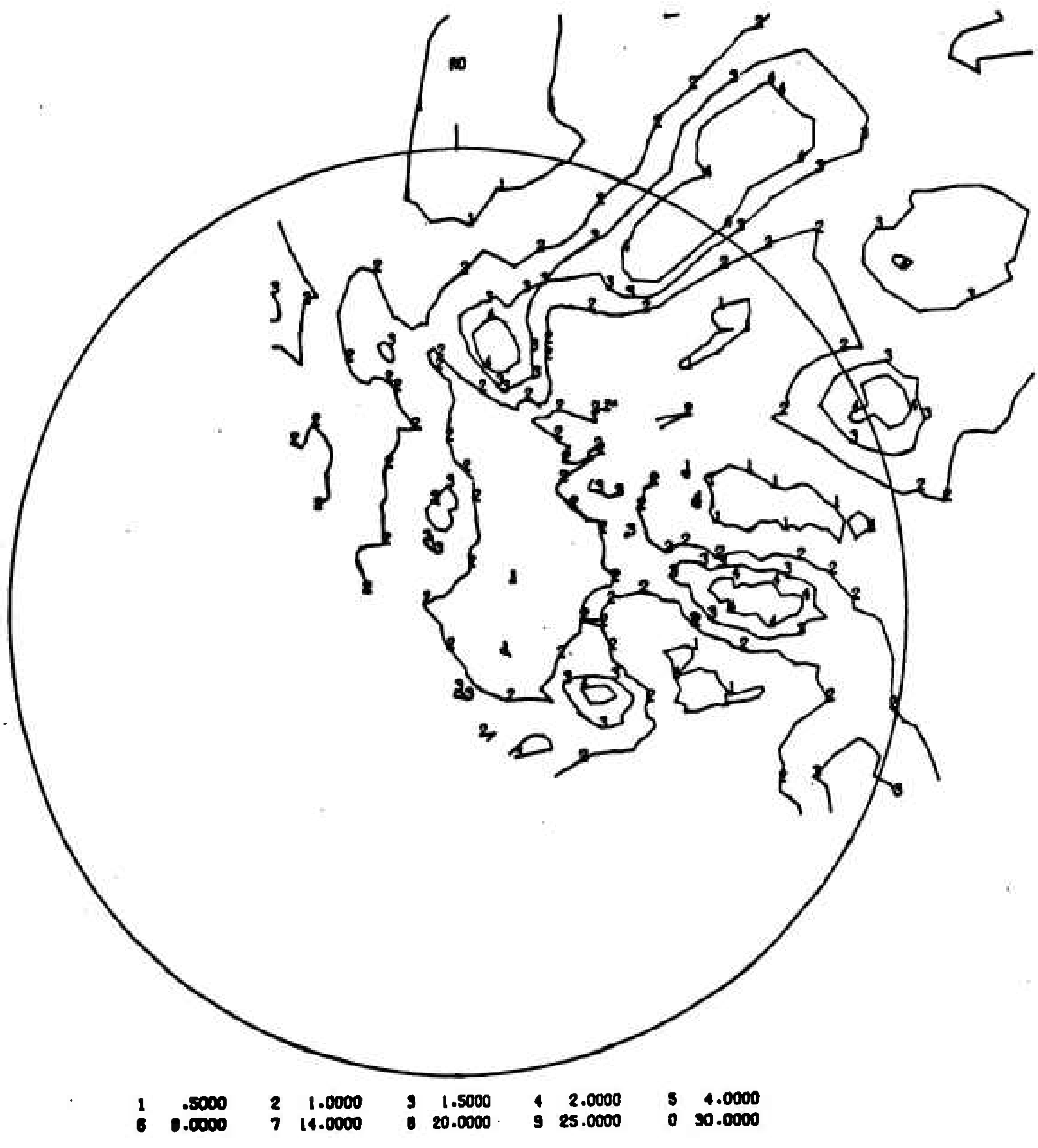


Figure 93c. Pole figure of alloy 334 (10Mo-6Cr-2.5Al) billet, (211) beta planes, LS plane with L orientated top to bottom of page (see Appendices D and F).

Figure 94 . Alloy 334(10Mo-6Cr-2.5Al). Solution treated 1300F-4 hr WQ, pre-aged 662F-70 hr. Note uniform distribution of α-clusters presumably resulting from precipitation on solute lean β′ zones.

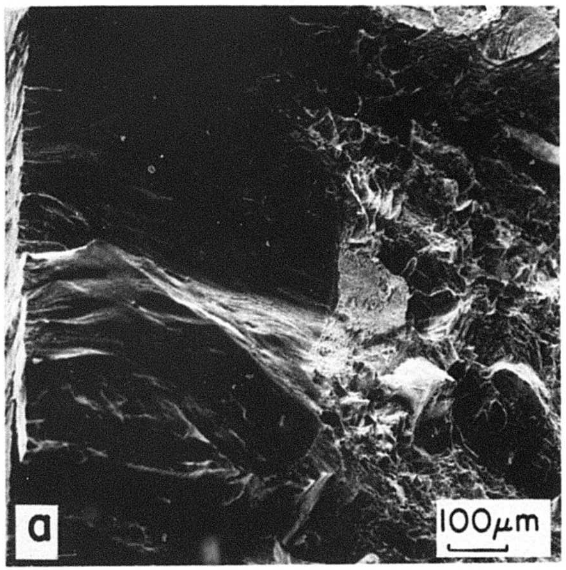
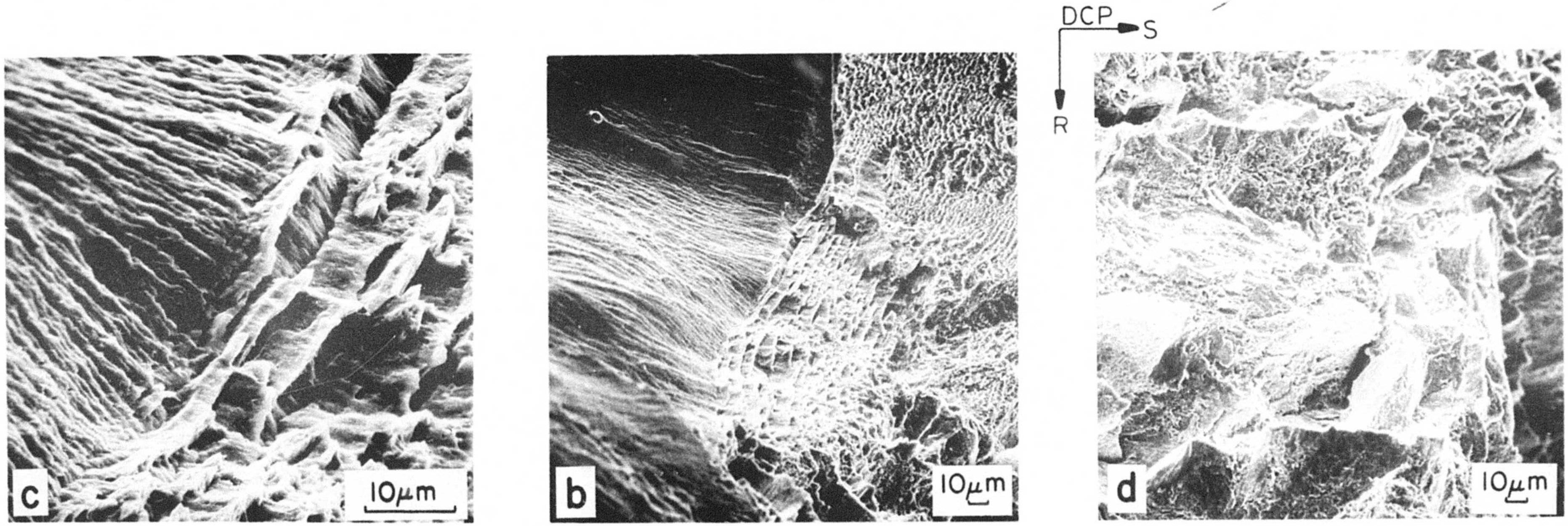


Figure 99 . Alloy 334(10Mo-6Cr-2.5Al), sample 4C1Y1. Solution treated 1350F-4 hr WQ, single aged 900F-96 hr. SEM of fracture surface: (a) X80, (b) X300, (c) X1500 - precrack/fast fracture transition, (d) X300 - fast fracture. YS(ksi): 186, RA(%): 23, K_Q(ksi√in): 86.



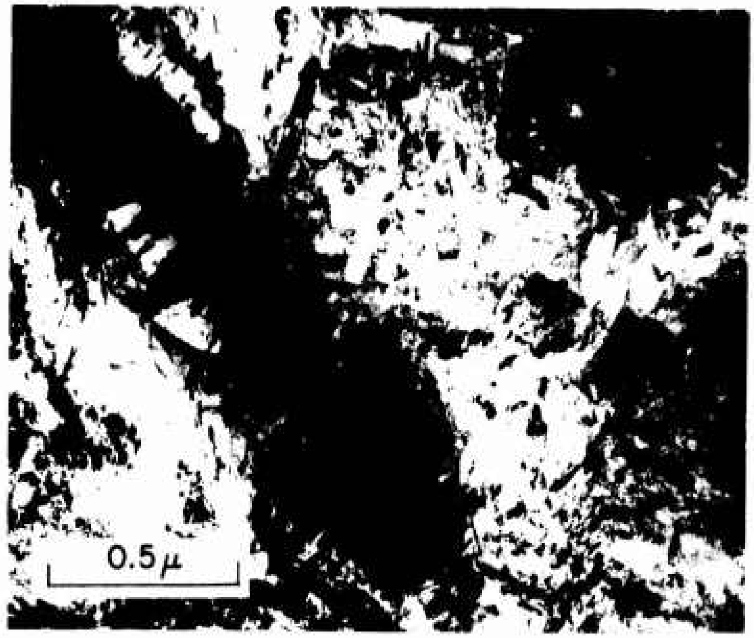


Figure 96 . Alloy 253(10Mo-8V-2.5Al), sample 3C3Y1. Solution treated 1275F-4 hr WQ, single aged 950F-96 hr. Note elongated primary alpha plates (~500Å thick) and precipitated alpha plates of the non-Burger's type.

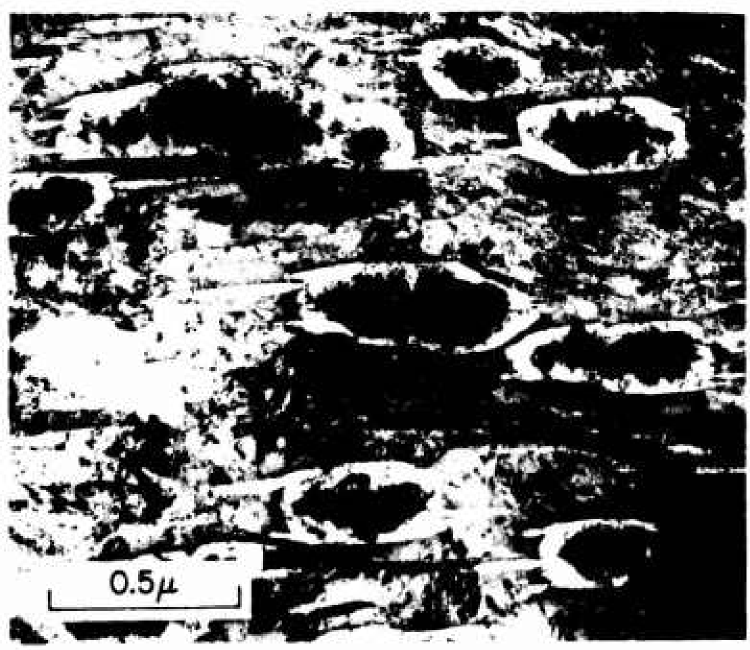


Figure 97 . Alloy 253(10Mo-8V-2.5Al), sample 3C321. Solution treated 1275F-4 hr WQ, duplex aged 750F-8 hr + 900F-8 hr. Compare with figure above. Note reduced aspect ratio of primary alpha and approximately same dispersion and size of precipitated alpha plates.

Figure 98 . Alloy 334(10Mo-6Cr-2.5Al), sample 4C1Y1. Solution treated 1350F-4 hr WQ, single aged 900F-96 hr. (Top) Grain boundard, primary and secondary alpha phase, the latter of the non-Burger's type. (Bottom) Precipitated alpha plates approximately 700 Å thick with an aspect ratio of up to 15:1.

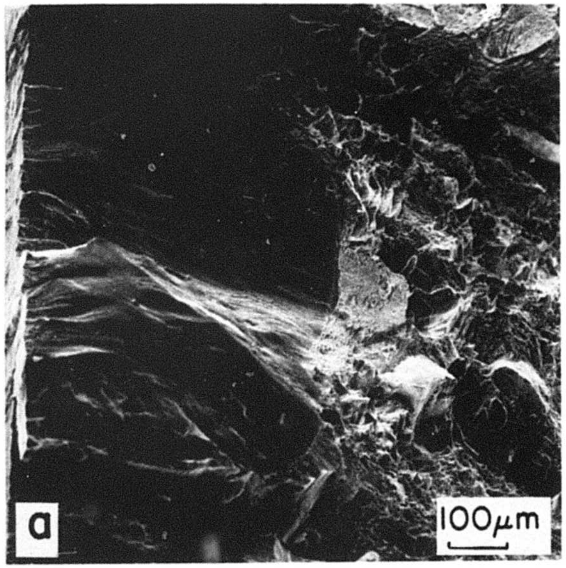
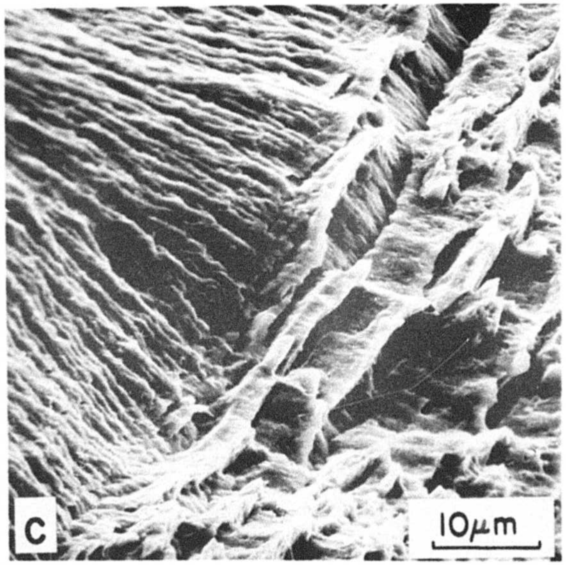
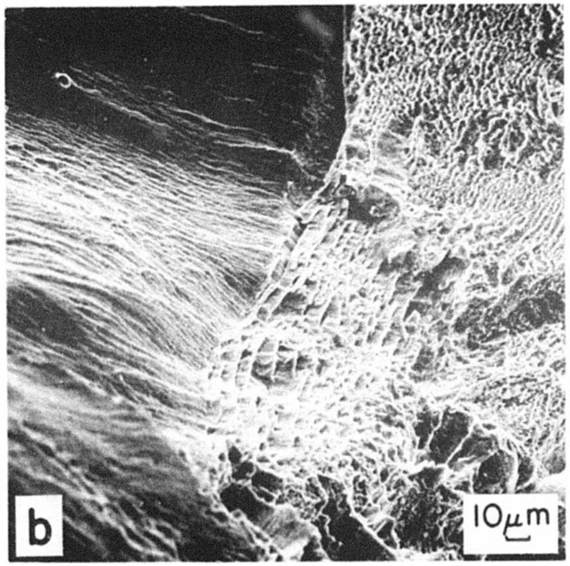
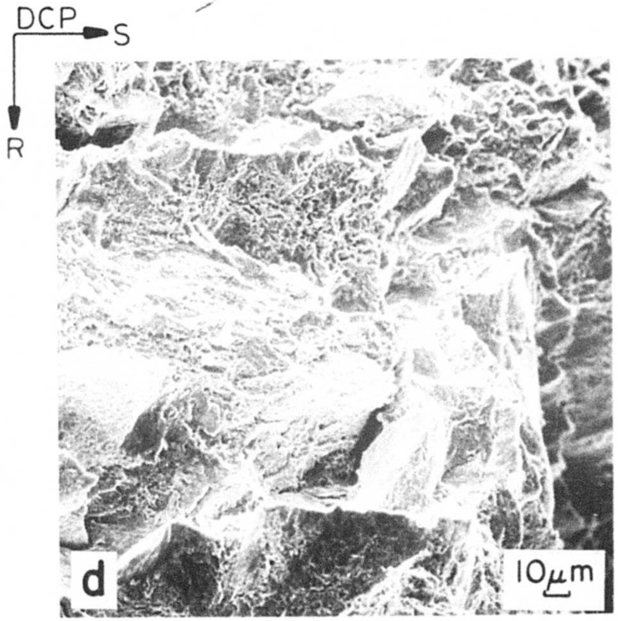


Figure 99 . Alloy 334(10Mo-6Cr-2.5Al), sample 4C1Y1. Solution treated 1350F-4 hr WQ, single aged 900F-96 hr. SEM of fracture surface: (a) X80, (b) X300, (c) X1500 - precrack/fast fracture transition, (d) X300 - fast fracture. YS(ksi): 186, RA(%): 23, K_Q(ksi√in): 86.







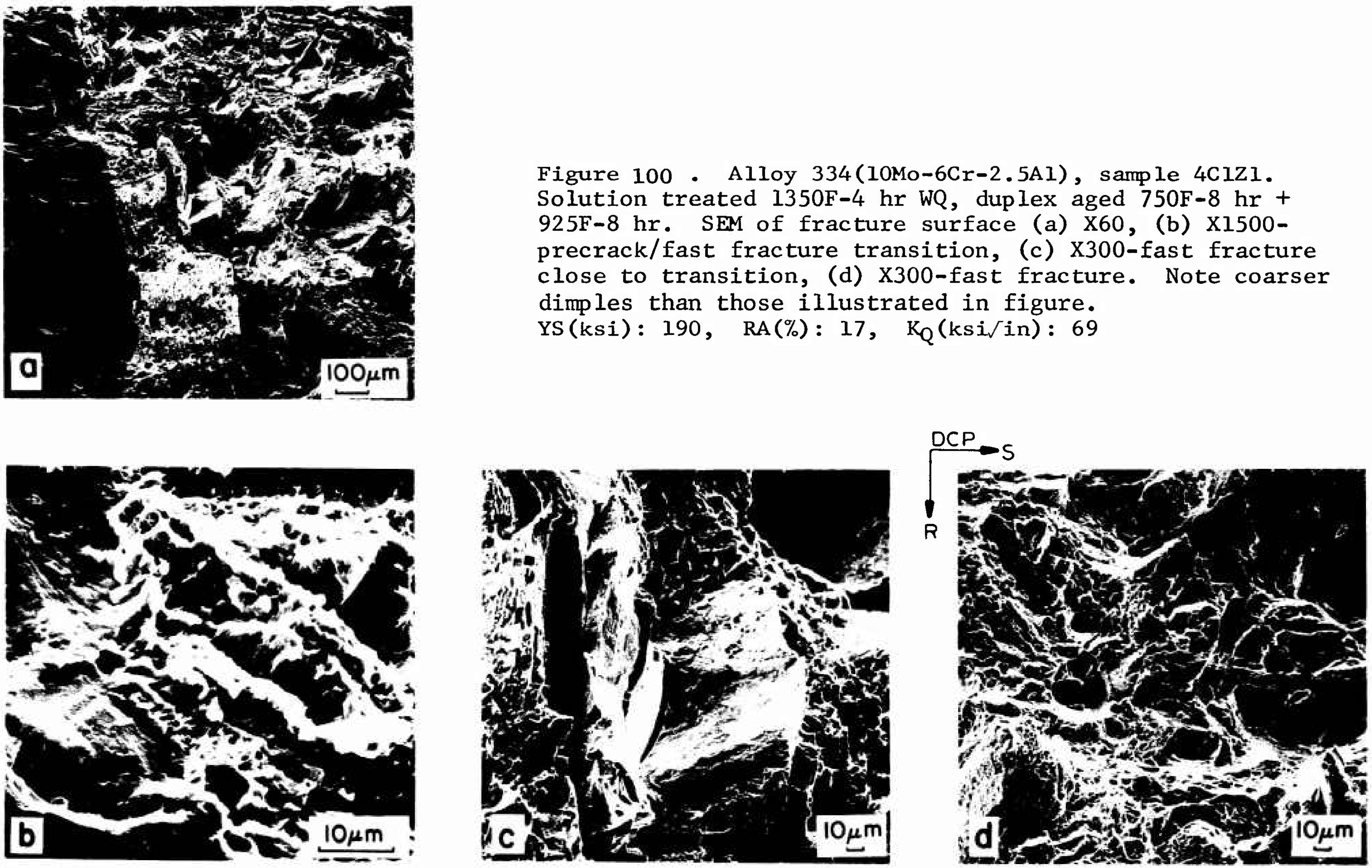


Figure 100 . Alloy 334(10Mo-6Cr-2.5Al), sample 4C1Z1. Solution treated 1350F-4 hr WQ, duplex aged 750F-8 hr + 925F-8 hr. SEM of fracture surface (a) X60, (b) X1500-precrack/fast fracture transition, (c) X300-fast fracture close to transition, (d) X300-fast fracture. Note coarser dimples than those illustrated in figure.
YS(ksi): 190, RA(%): 17, $K_Q(ksi\sqrt{in})$: 69

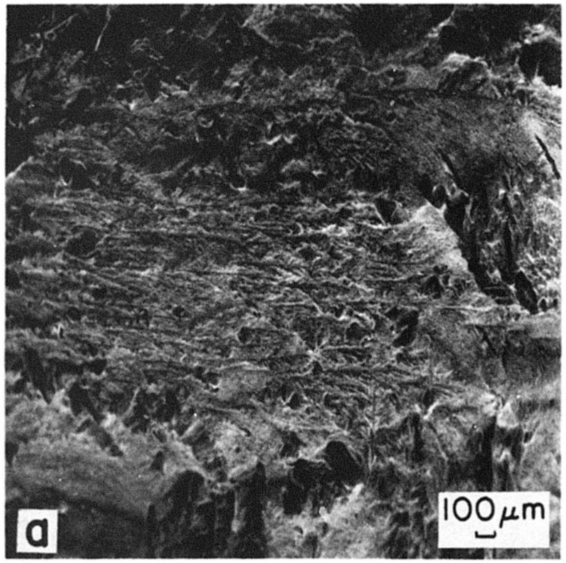
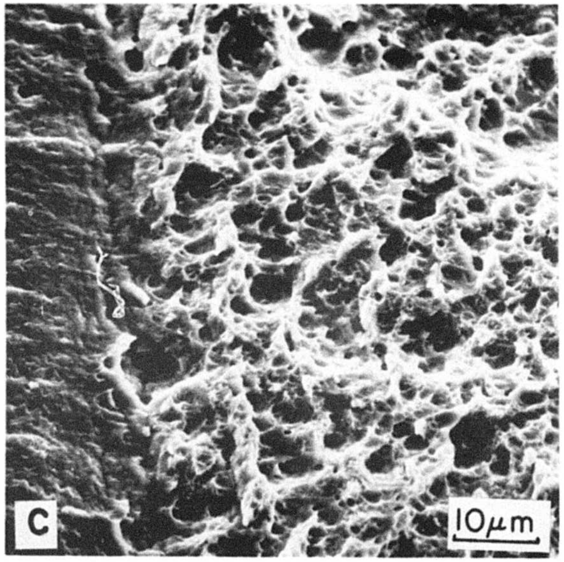
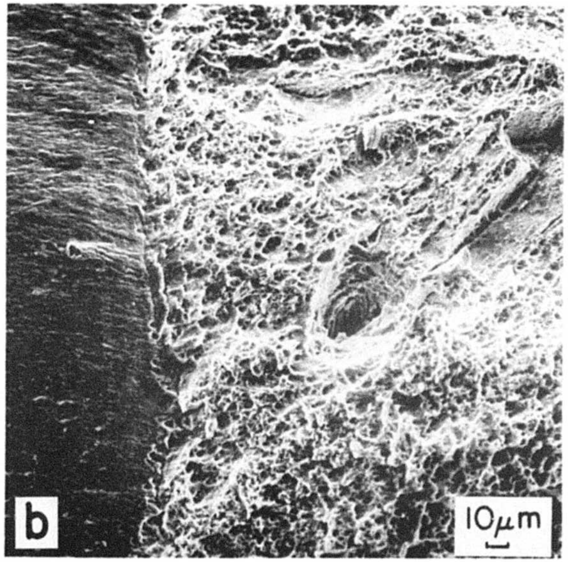
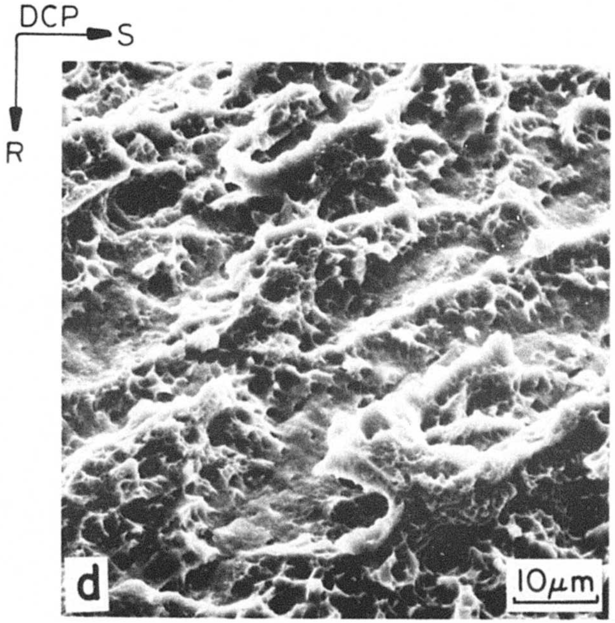


Figure 101. Alloy 253(10Mo-8V-2.5Al), sample 3C3Y1. Solution treated 1275F-4 hr WQ, single aged 950F-96 hr. SEM of fracture surface (a) X25, (b) X300, (c) X1200 - precrack/fast fracture transition, (d) X1200 - fast fracture.
YS(ksi): 157, RA(%): 33, K_Q(ksi$\sqrt{in}$): 104







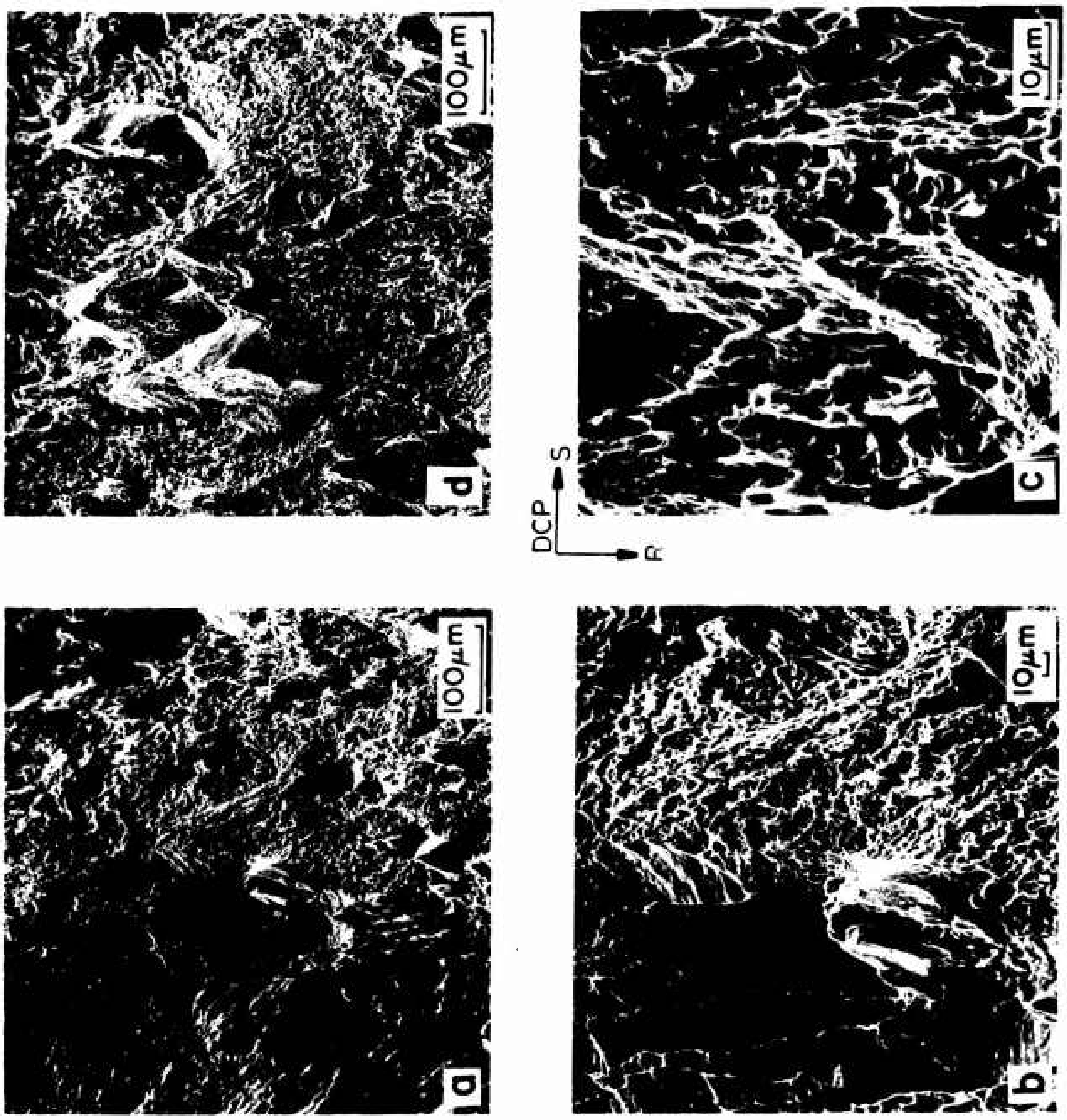


Figure 102 . Alloy 253(10Mo-8V-2.5Al), sample 3C3Z1. Solution treated 1275F-4 hr WQ, duplex aged 750F-8 hr + 900F-8 hr. SEM of fracture surface (a) X120, (b) X300 - precrack/fast fracture transition, (c) X1200, (d) X120 - fast fracture.
YS(ksi): 170, RA(%): 22, K_Q(ksi$\sqrt{\text{in}}$: 75.

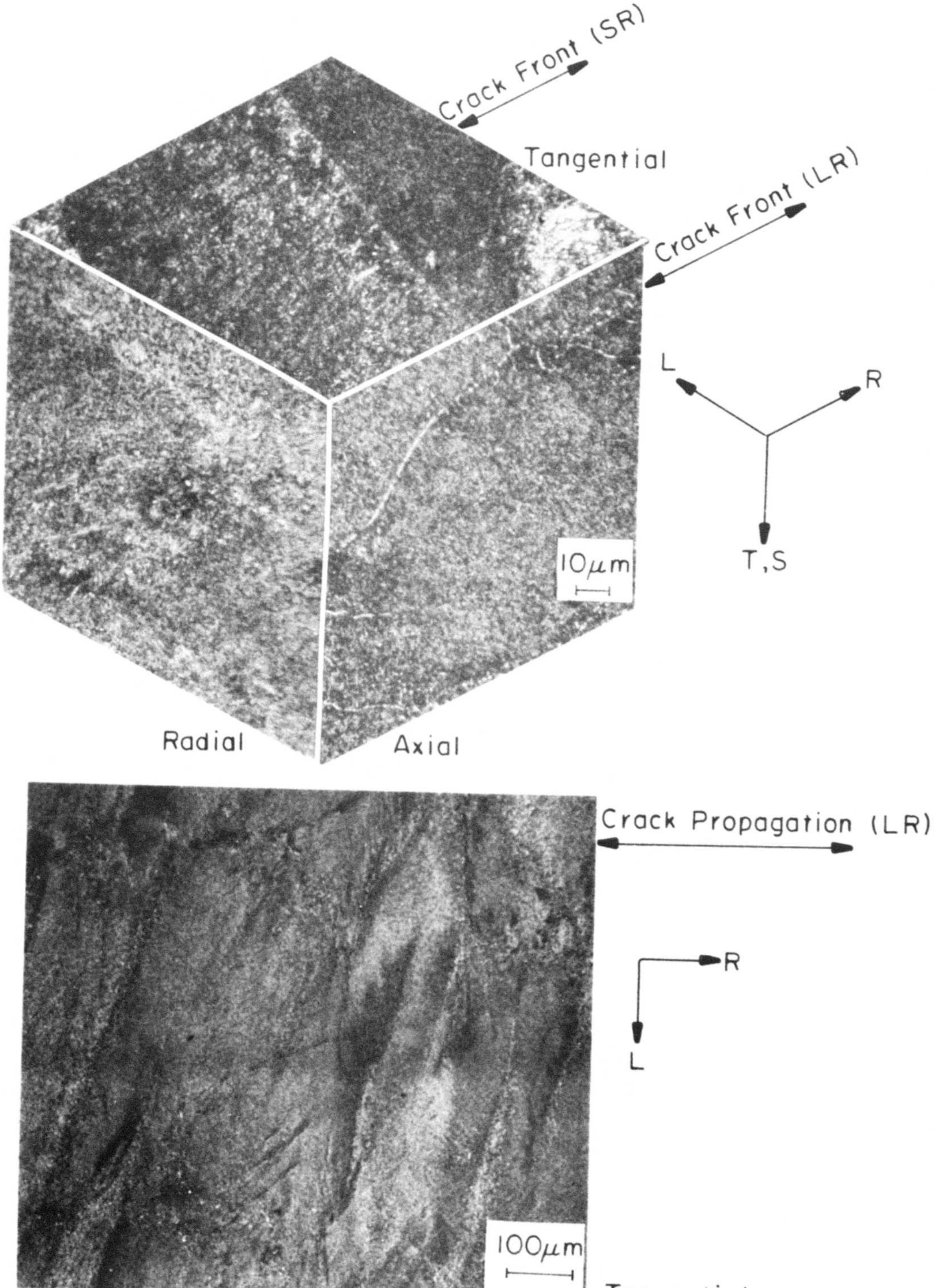


Figure 103. Alloy 334(10Mo-6Cr-2.5Al), six inch billet slice, samples 4ELR10 and 4ESR2 (Table XLVII). Solution treated 1300F-4 hr WQ, aged 900F-96 hr. Isometric X500, tangential face X100.

YS(ksi):	183 (L)	RA(%):	15 (L)	K (ksi$\sqrt{in}$):	84 (LR)
	185 (T)		4 (T)		57 (SR)

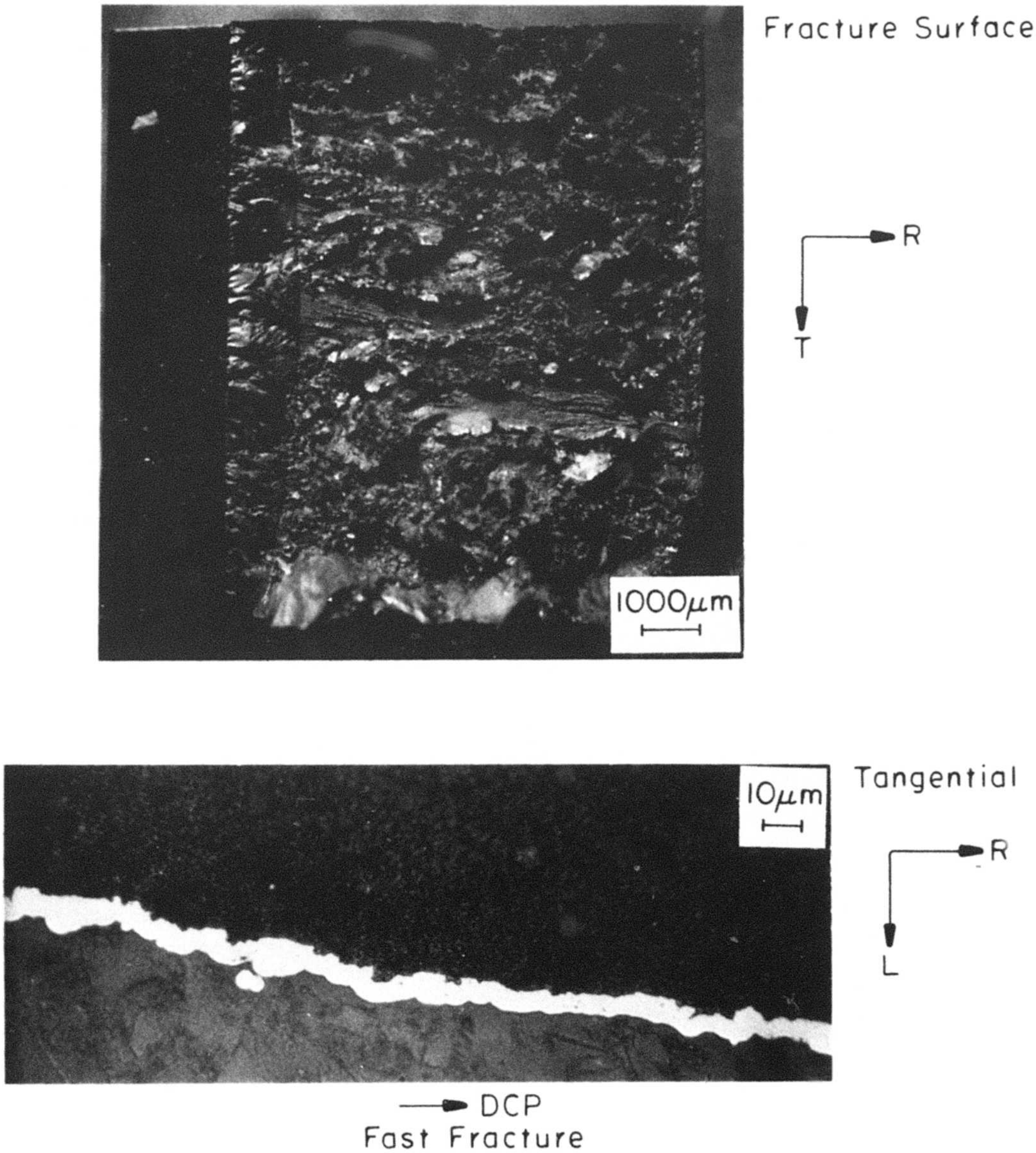


Figure 104 . Alloy 334, sample 4ELR10. Fracture surface X8, crack path X500.

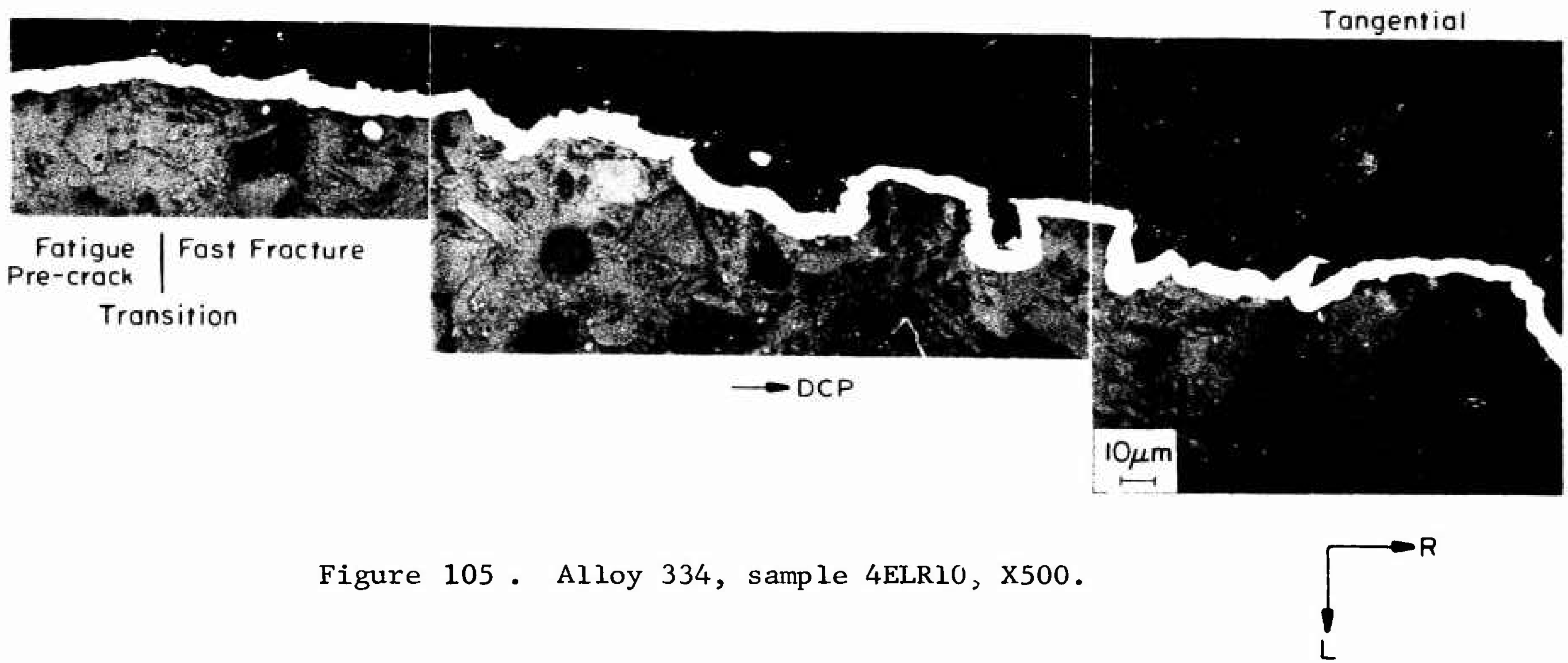


Figure 105 . Alloy 334, sample 4ELR10, X500.

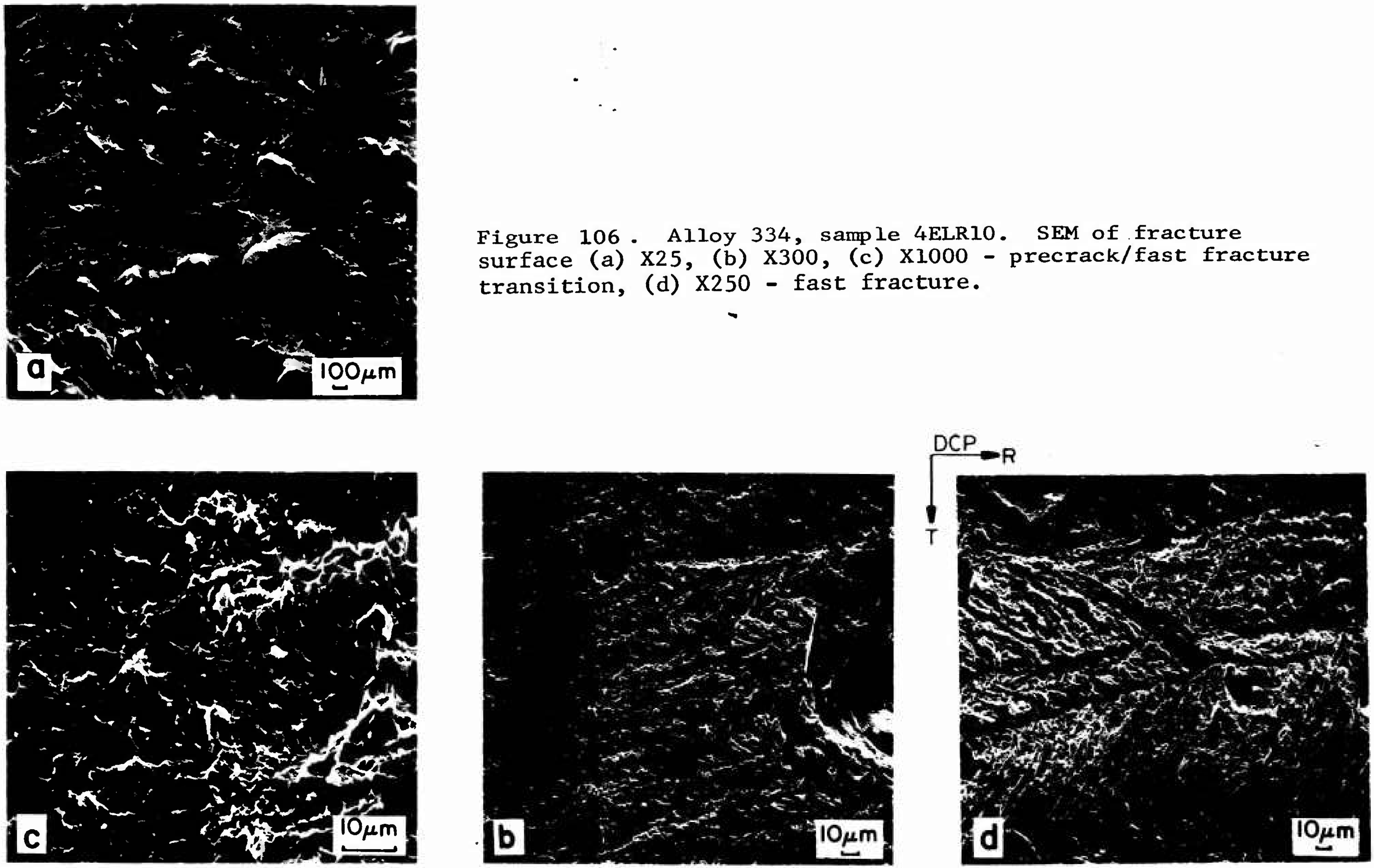
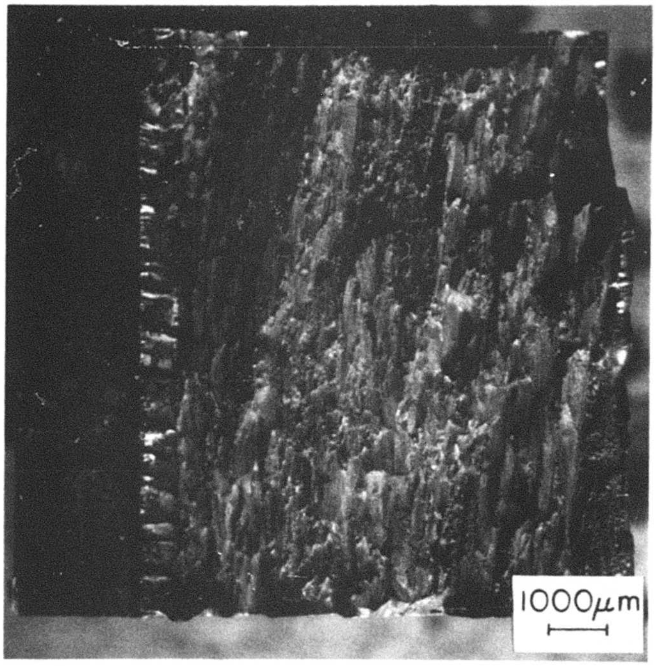


Figure 106. Alloy 334, sample 4ELR10. SEM of fracture surface (a) X25, (b) X300, (c) X1000 - precrack/fast fracture transition, (d) X250 - fast fracture.



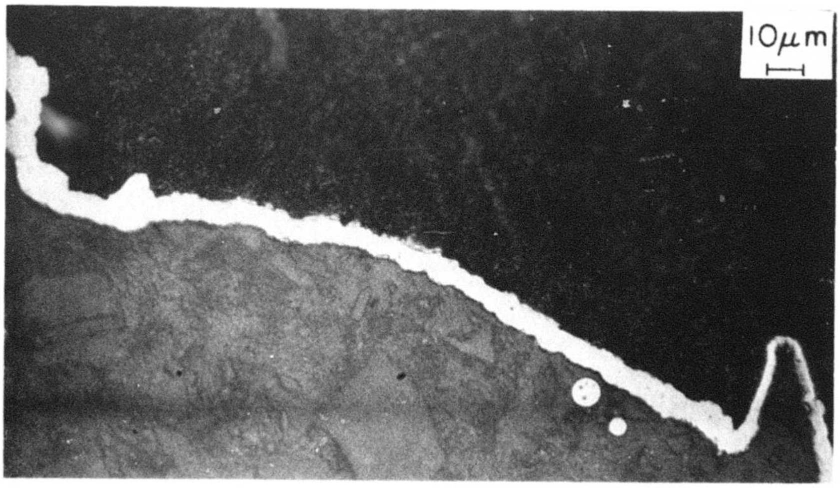
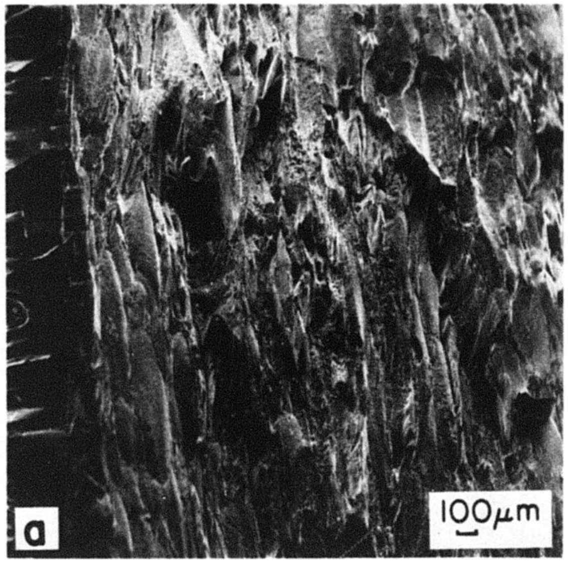


Figure 107 . Alloy 334, sample 4ESR2. Fracture surface X8, crack path X500.



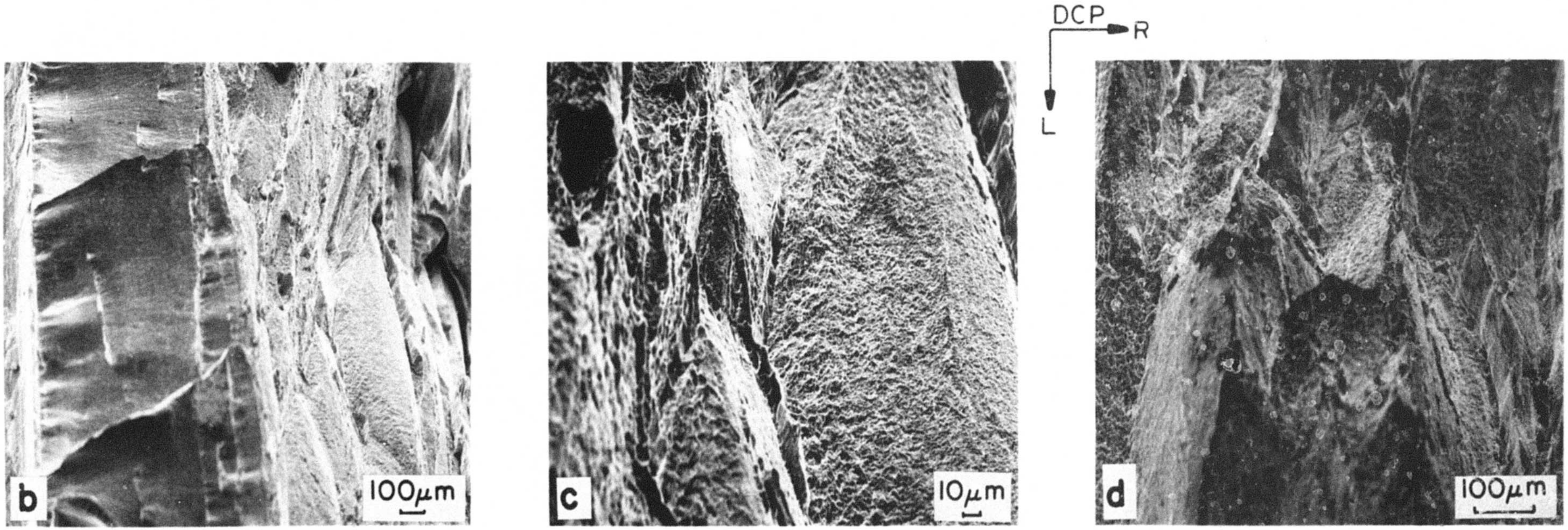
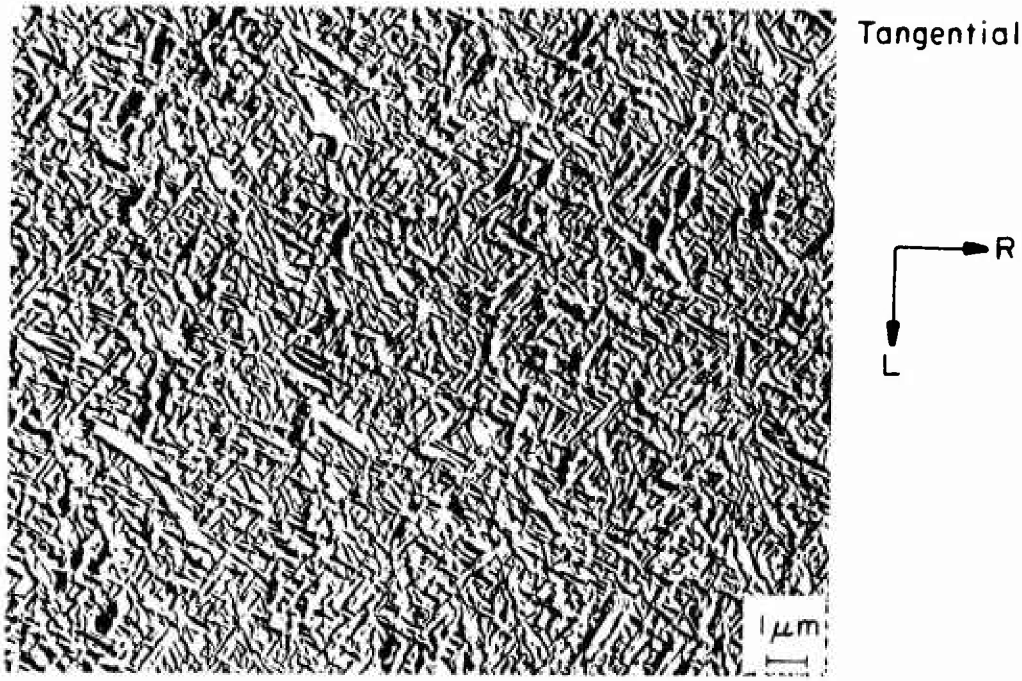


Figure 108 . Alloy 334, sample 4ESR2. SEM of fracture surface (a) X25, (b) X40 - precrack/fast fracture transition, (c) X300 - fast fracture close to transition, (d) X100 - fast fracture.



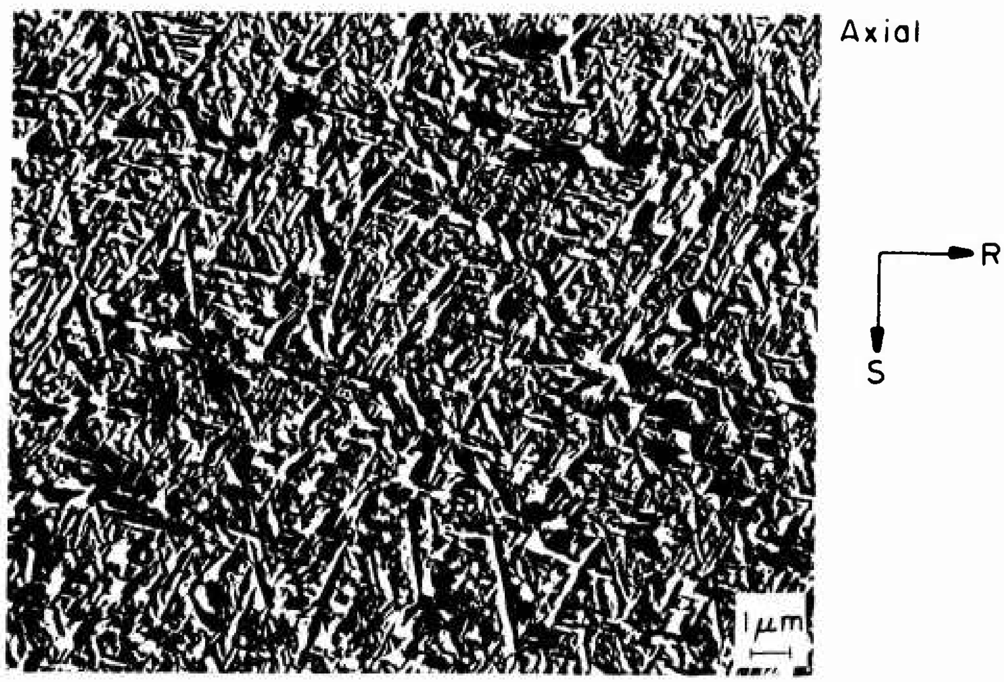


Figure 109 . Alloy 334 surface replicas X5200 (top) sample 4ELR10, (bottom) sample 4ESR2.

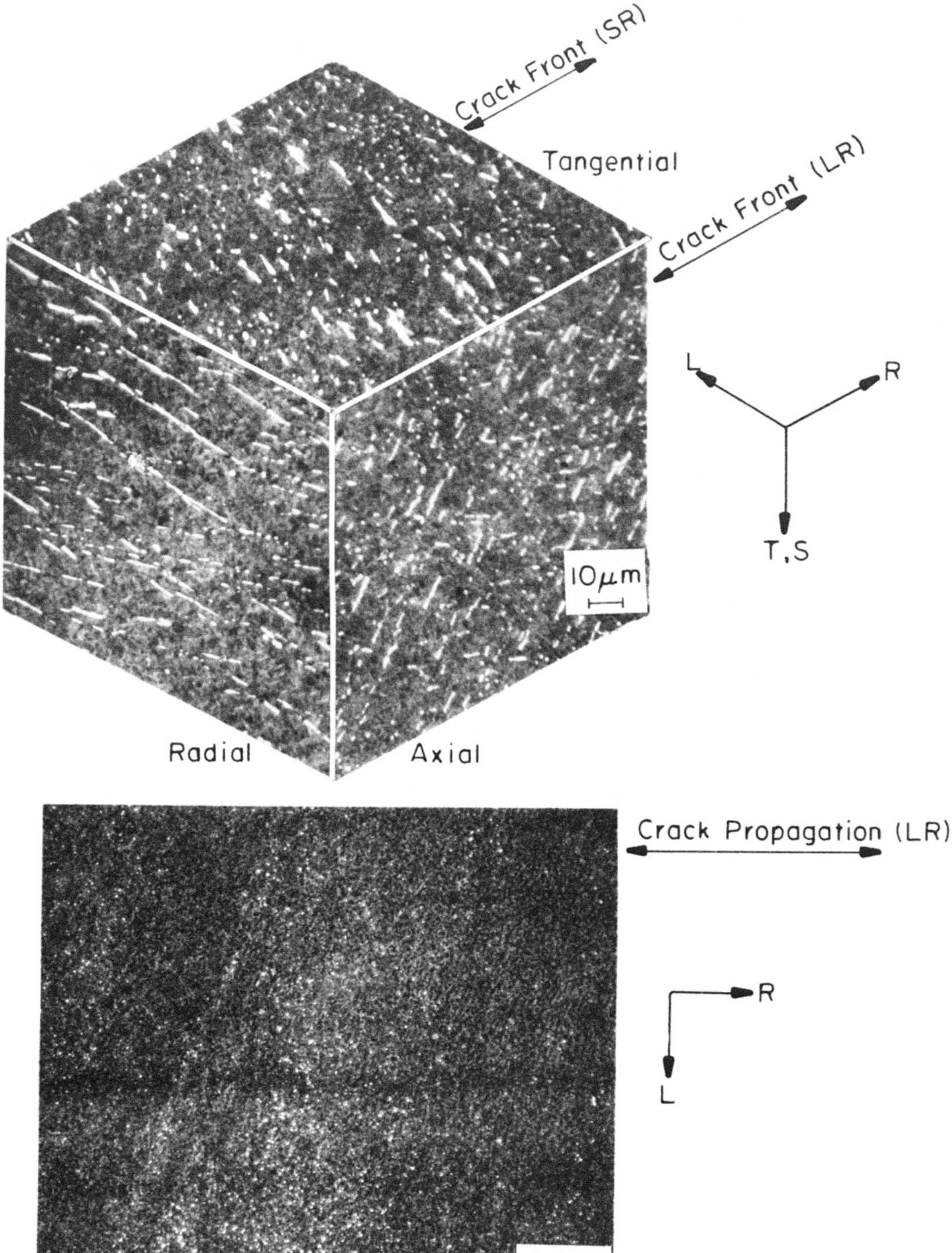


Figure 110 . Alloy 227(7Mo-4Cr-2.5Al) six inch billet slice, samples 7ELR11 and 7ESR3 (Table XLVIII). Solution treated 1475F-2 hr WQ, aged 1025F-8 hr. Isometric X500, tangential face X100.

YS(ksi):	174 (L)	RA(%):	24 (L)	K_Q(ksi$\sqrt{in}$):	59 (LR)
	171 (T)		12 (T)		51 (SR)

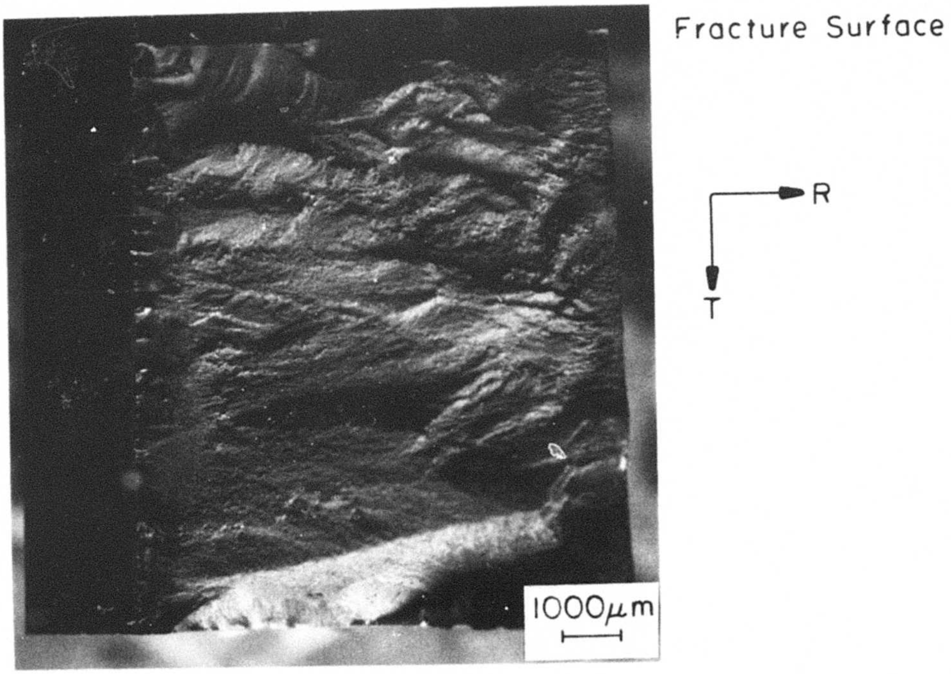


Figure 111 . Alloy 227, sample 7ELR11. Fracture surface X8.

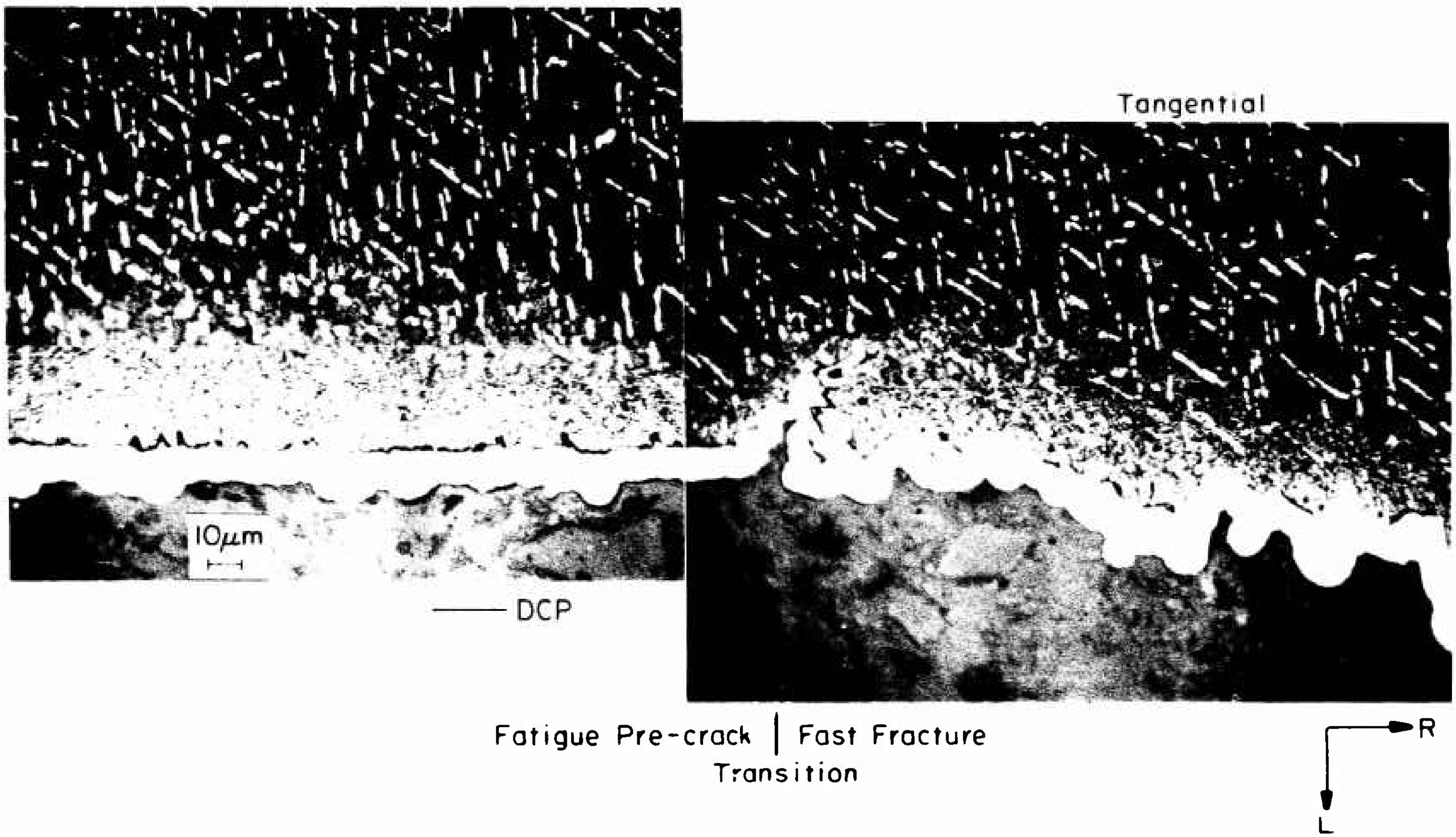


Figure 112 . Alloy 227, sample 7ELR11, X500.

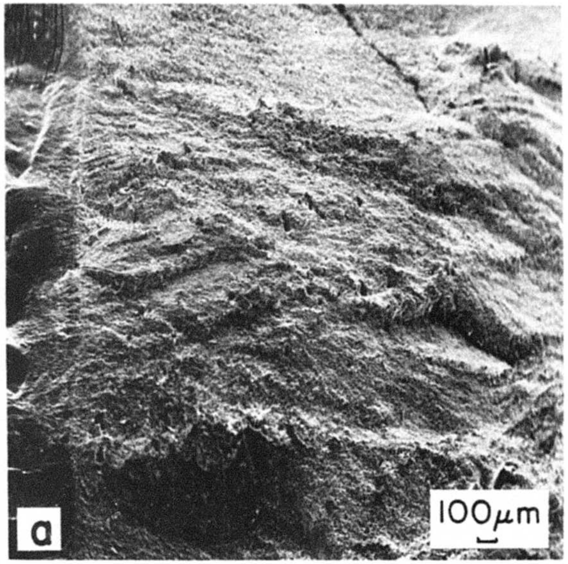
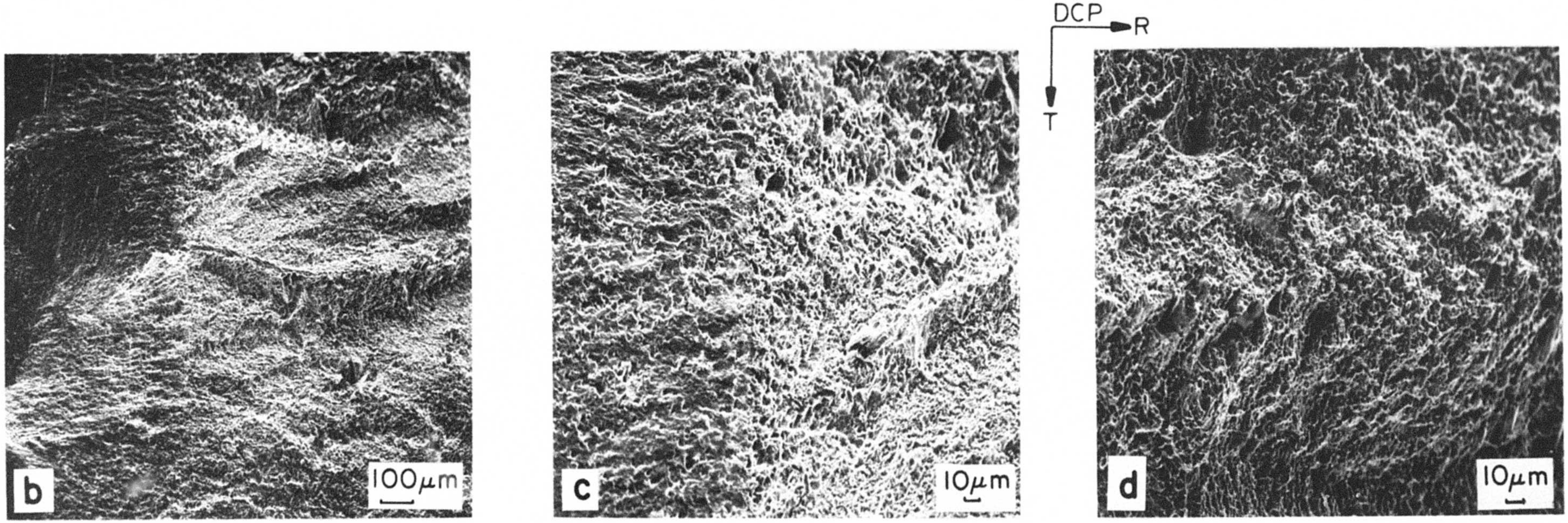


Figure 113 . Alloy 227, sample 7ELR11. SEM of fracture surface (a) X25, (b) X50, (c) X250 - precrack/fast fracture transition, (d) X300 - fast fracture.



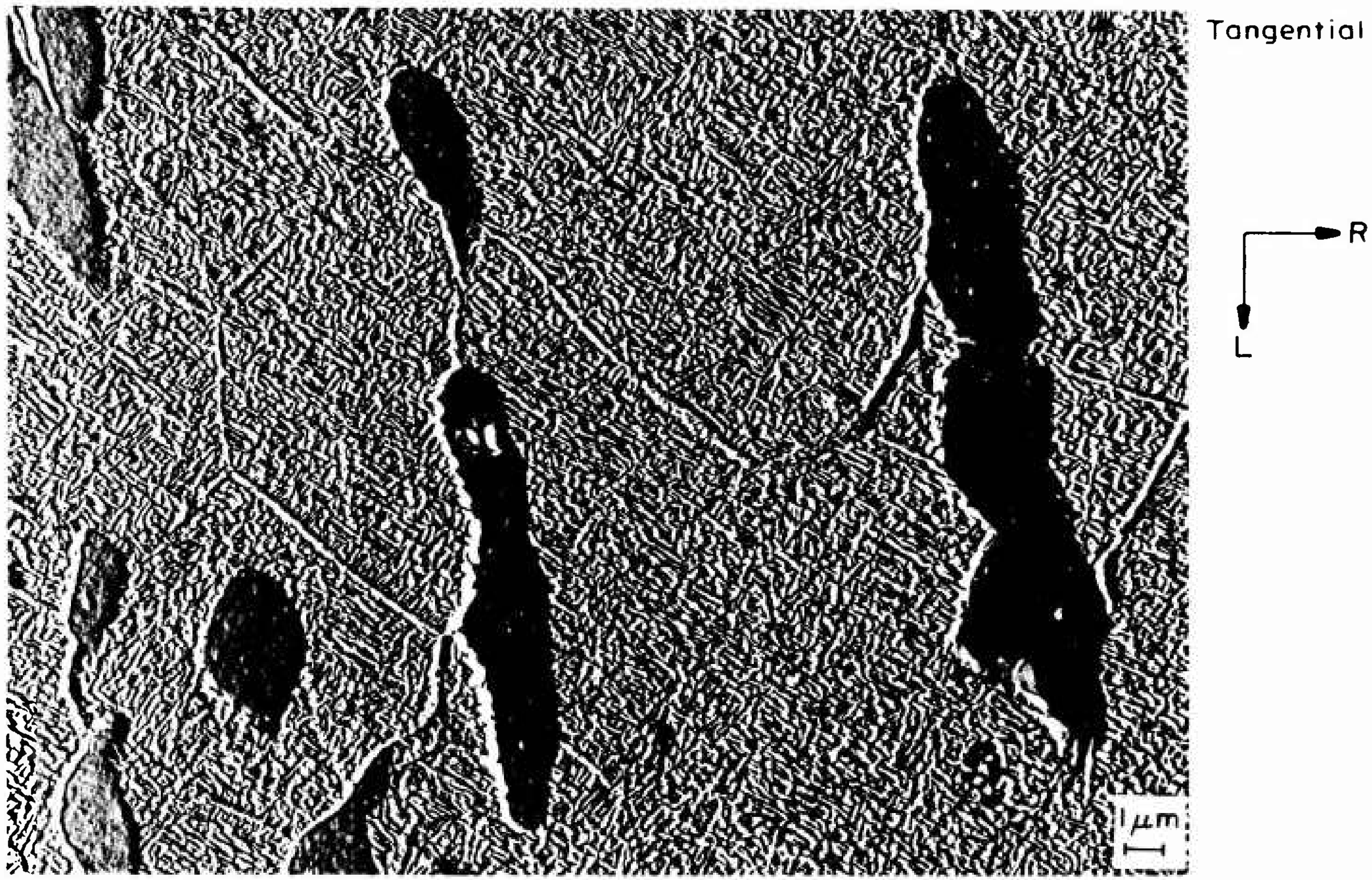


Figure 114 . Alloy 227, sample 7ELR11, surface replica X5200.

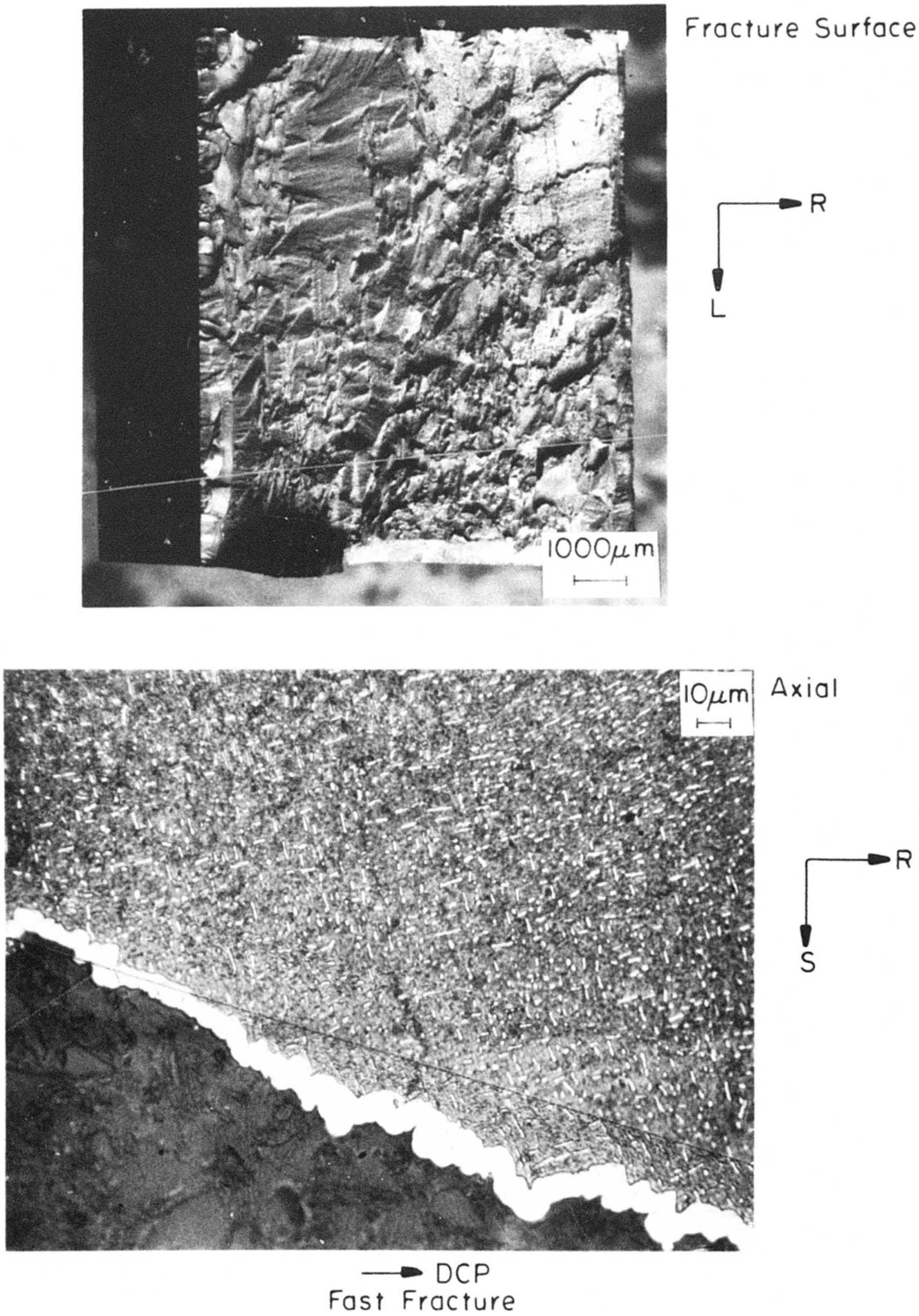


Figure 115. Alloy 227, sample 7ESR3. Fracture surface X8, crack path X500.

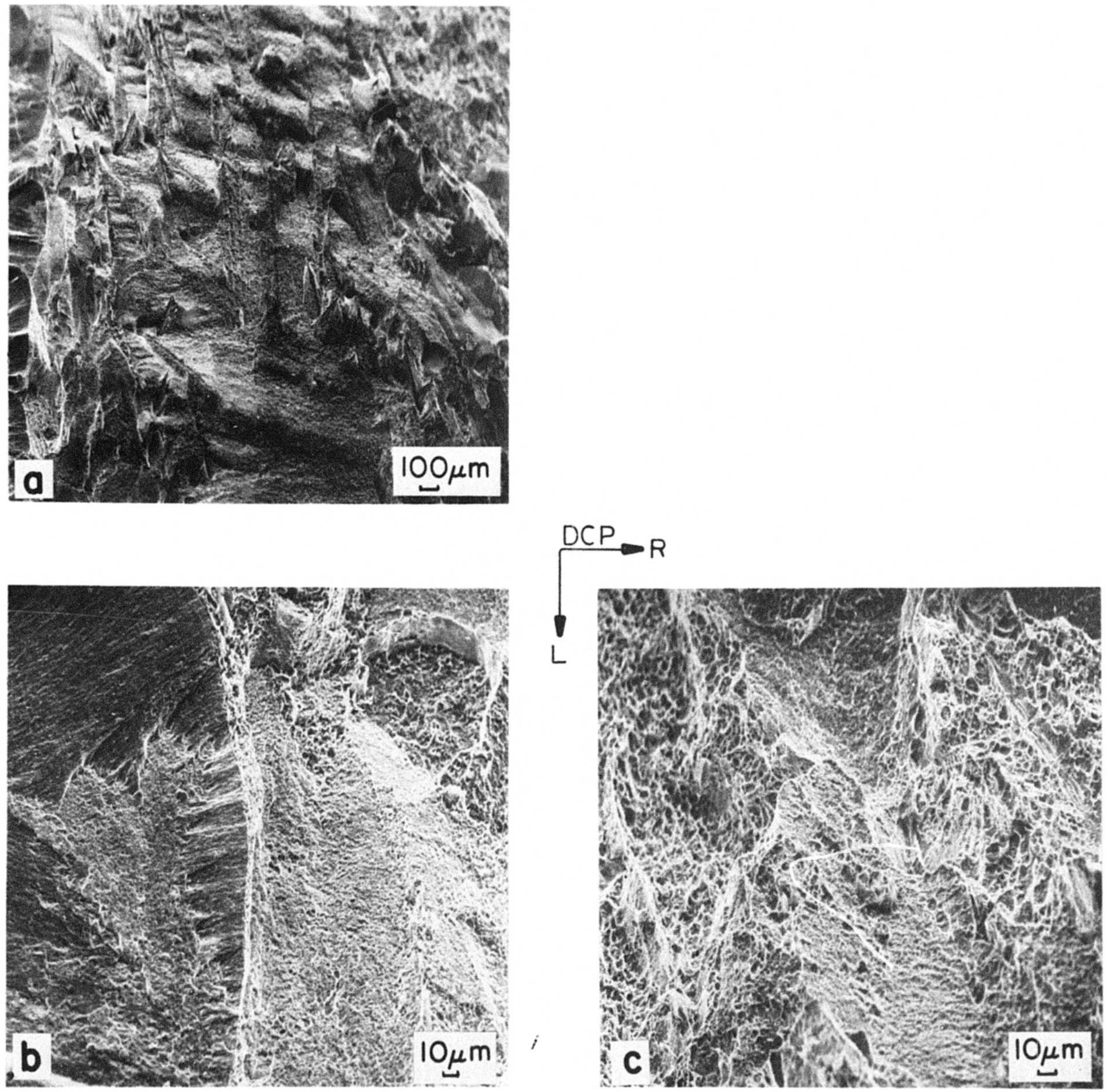


Figure 116. Alloy 227, sample 7ERS3. SEM of fracture surface (a) X25, (b) X200 - precrack/fast fracture transition, (c) X250 - fast fracture.

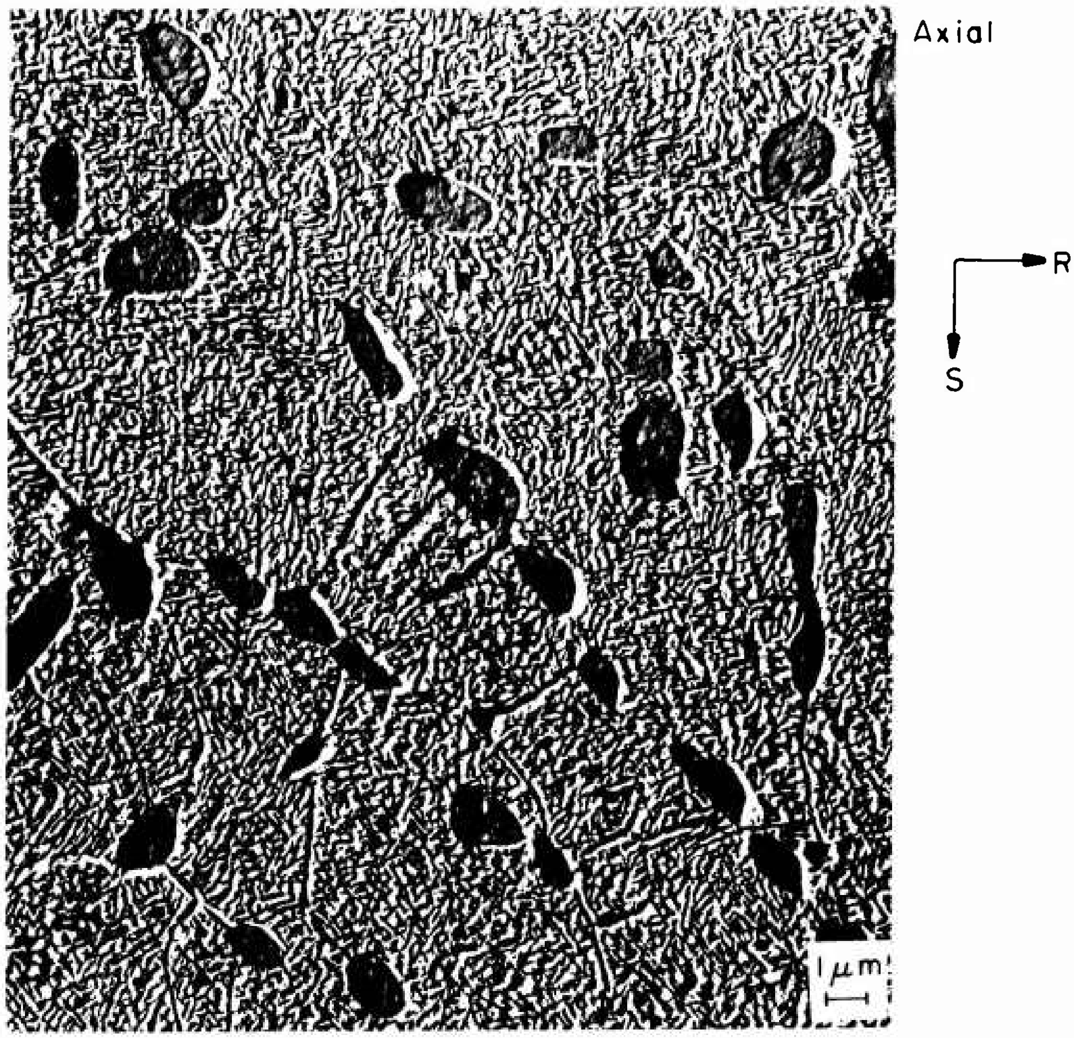


Figure 117. Alloy 227, sample 7ESR3, surface replica X5200.

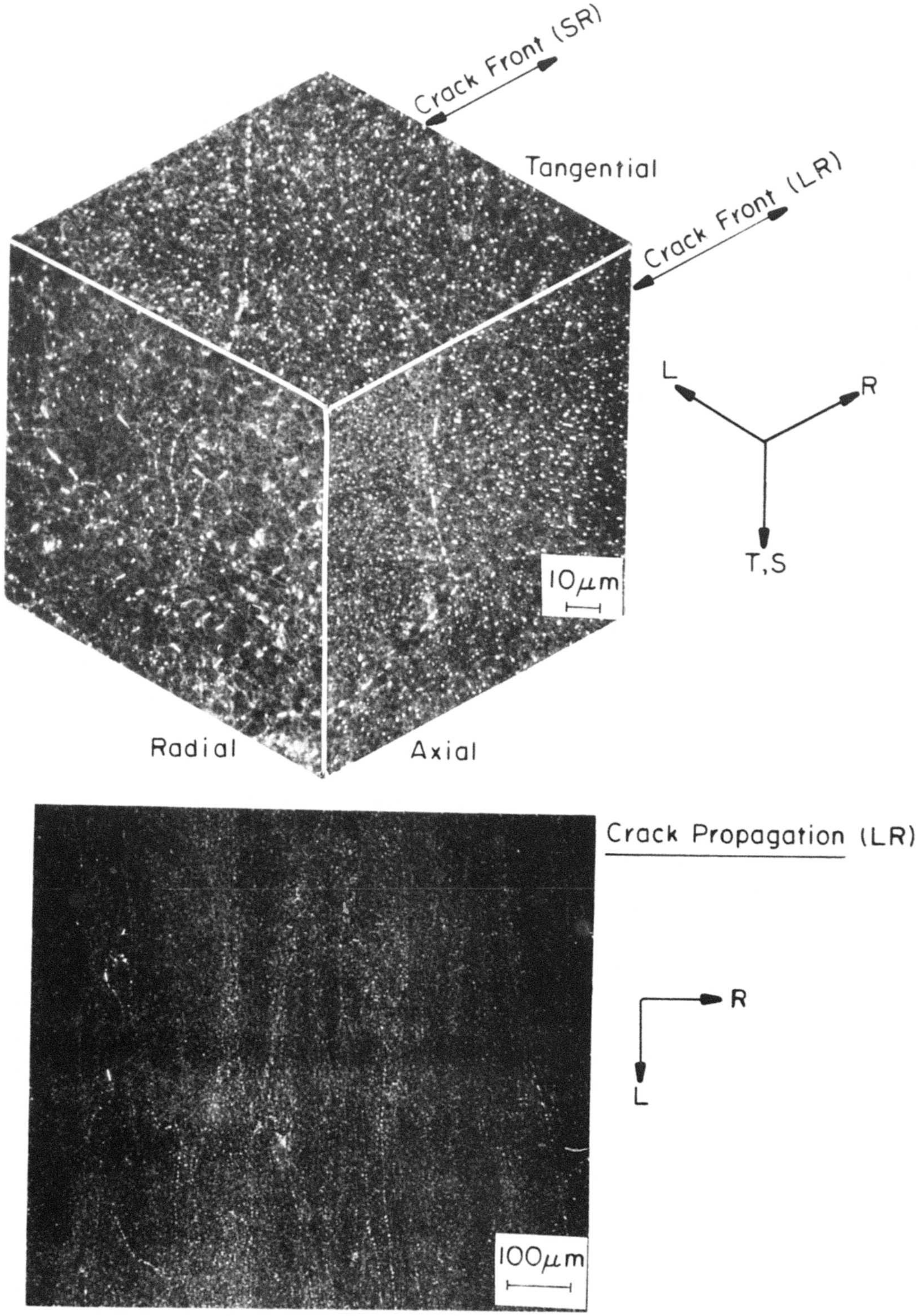
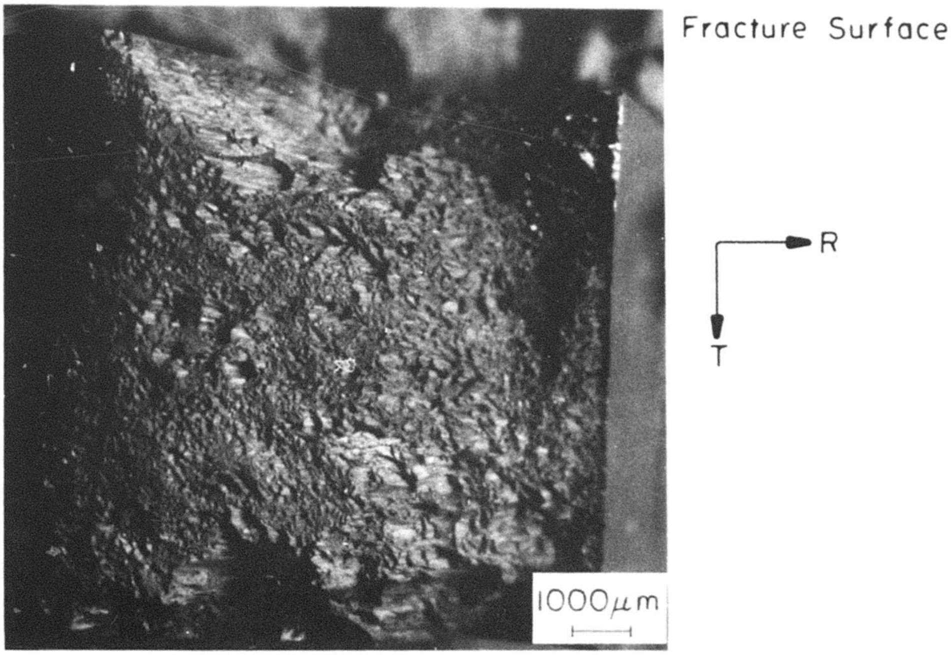


Figure 118 . Alloy 227(7Mo-4Cr-2.5Al) six inch billet slice, samples 7ELR9 and 7ESR1 (Table XLVIII). Solution treated 1475F-2 hr WQ, aged 900F-96 hr + 1050F-8 hr. Isometric X500, tangential face X100.

YS(ksi):	183 (L)	RA(%):	28 (L)	K_Q(ksi$\sqrt{\text{in}}$):	78 (LR)
	183 (T)		6 (T)		41 (SR)



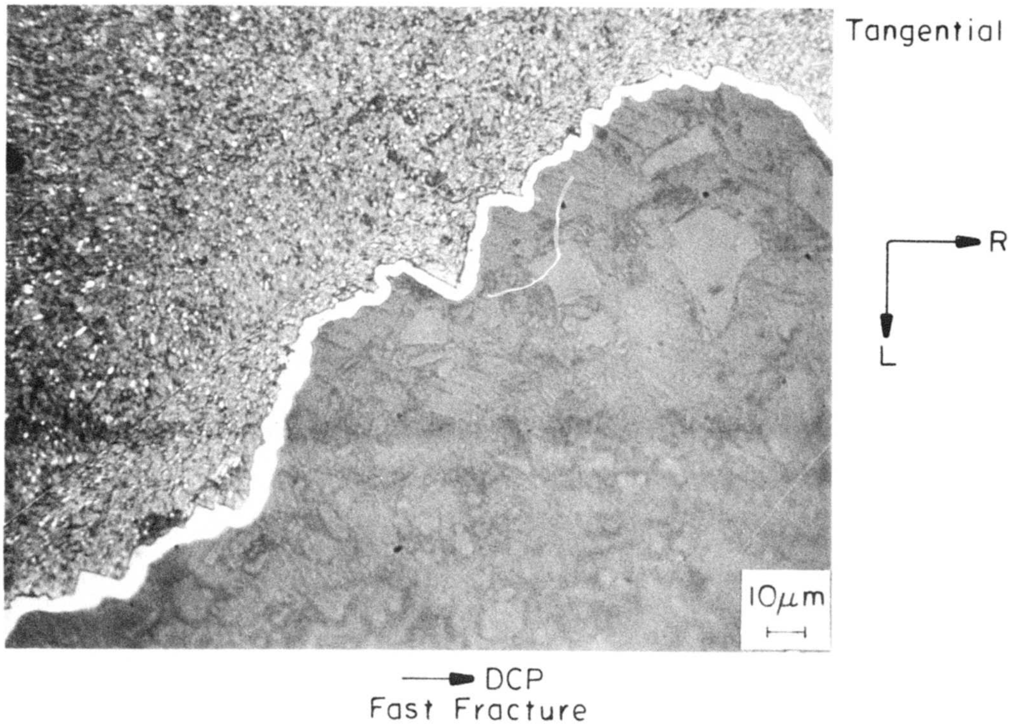


Figure 119 . Alloy 227, sample 7ELR9. Fracture surface X8, crack path X500.

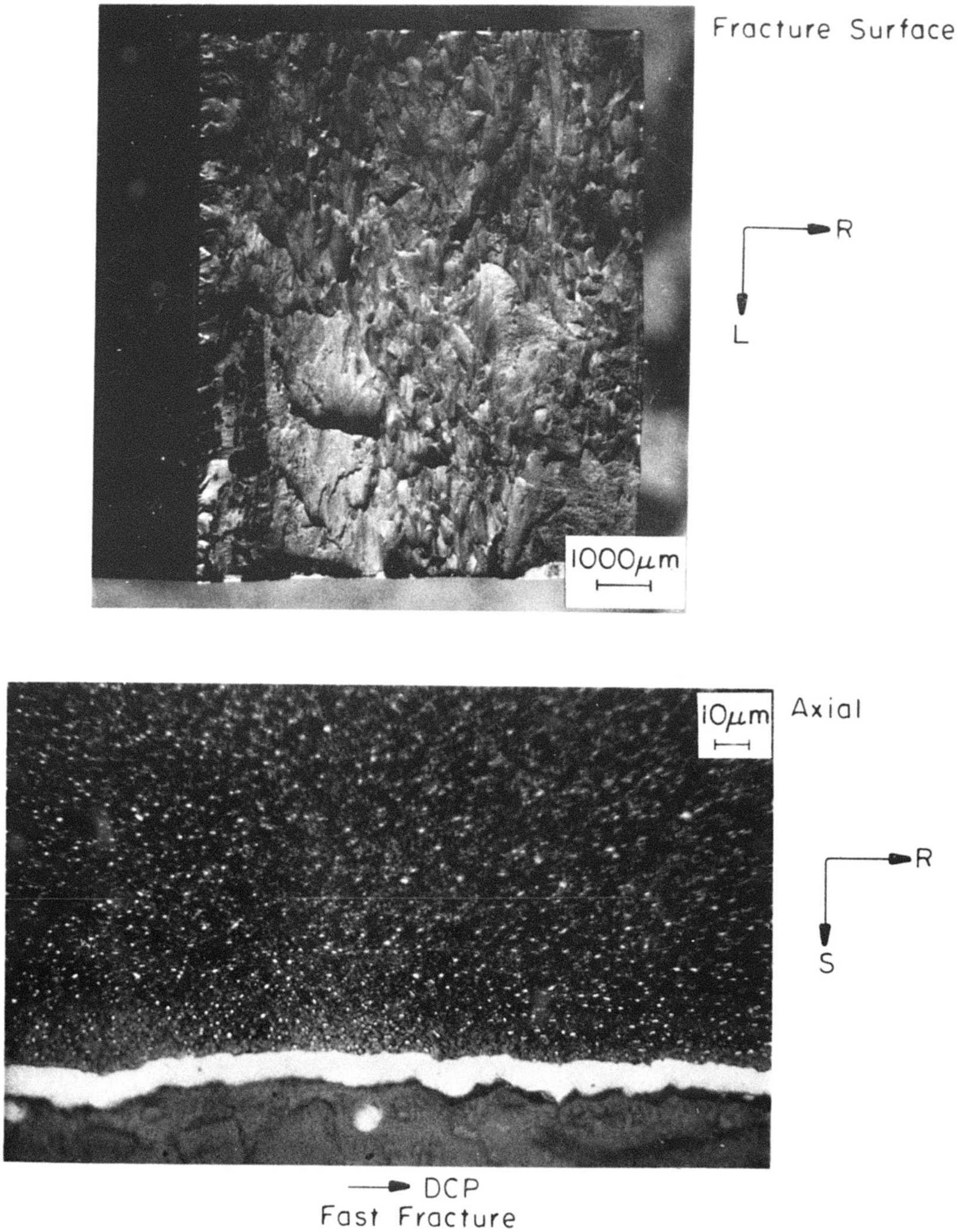
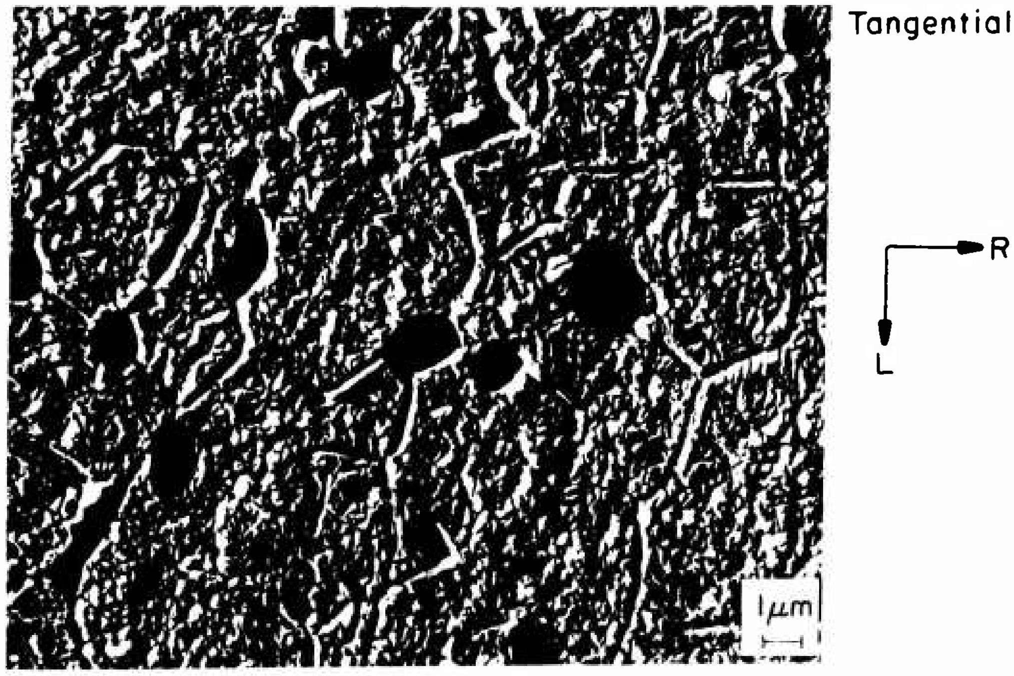


Figure 120 . Alloy 227, sample 7ESR1. Fracture surface X8, crack path X500.



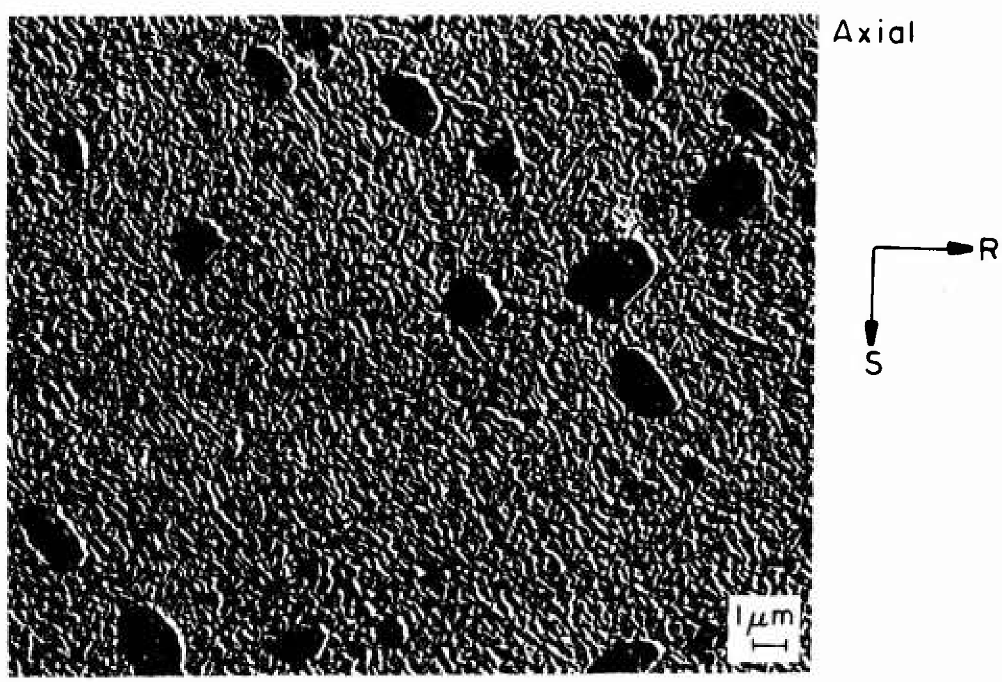


Figure 121 . Alloy 227 surface replicas X5200. (Top) sample 7ELR9, (Bottom) sample 7ESR1.

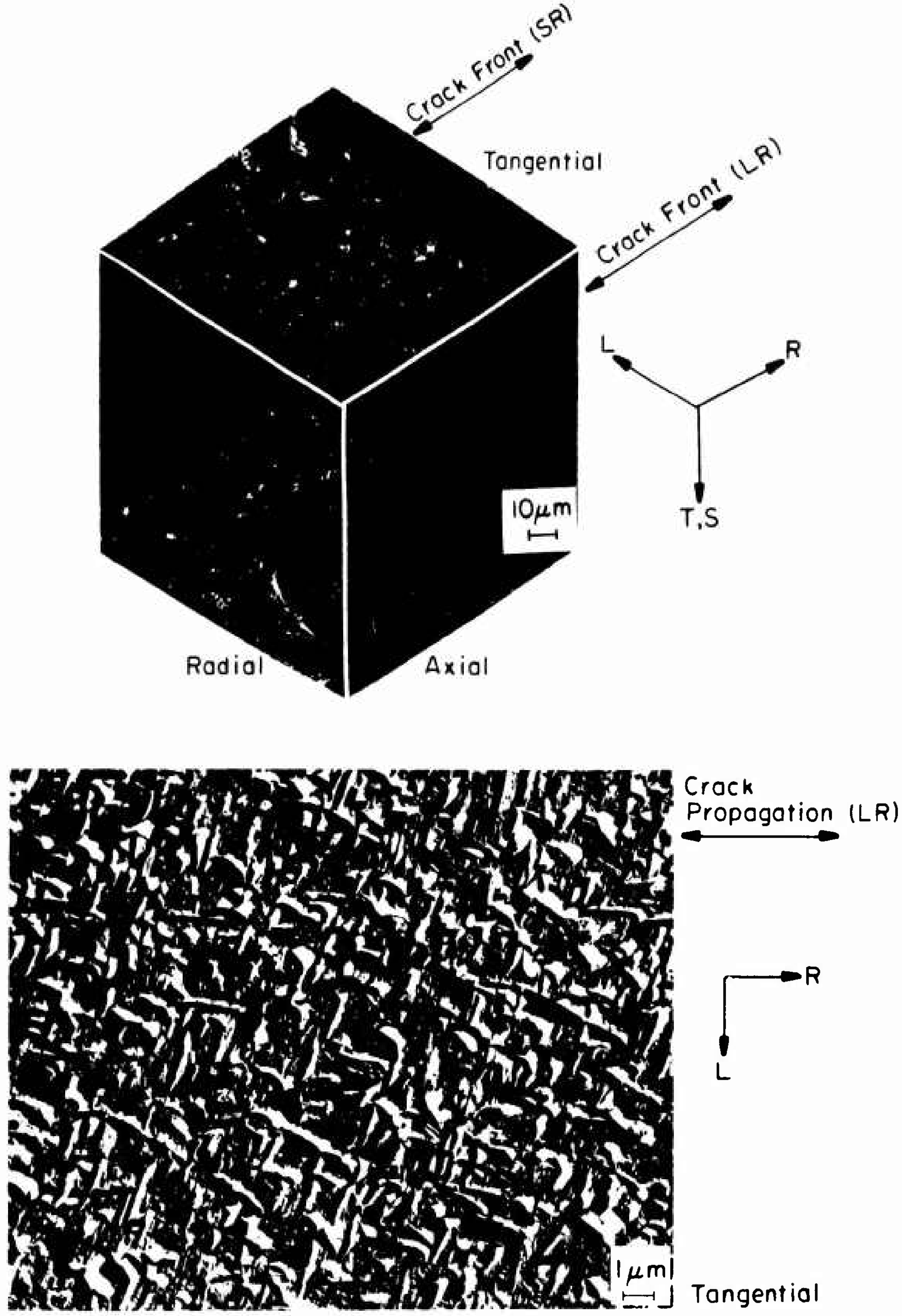
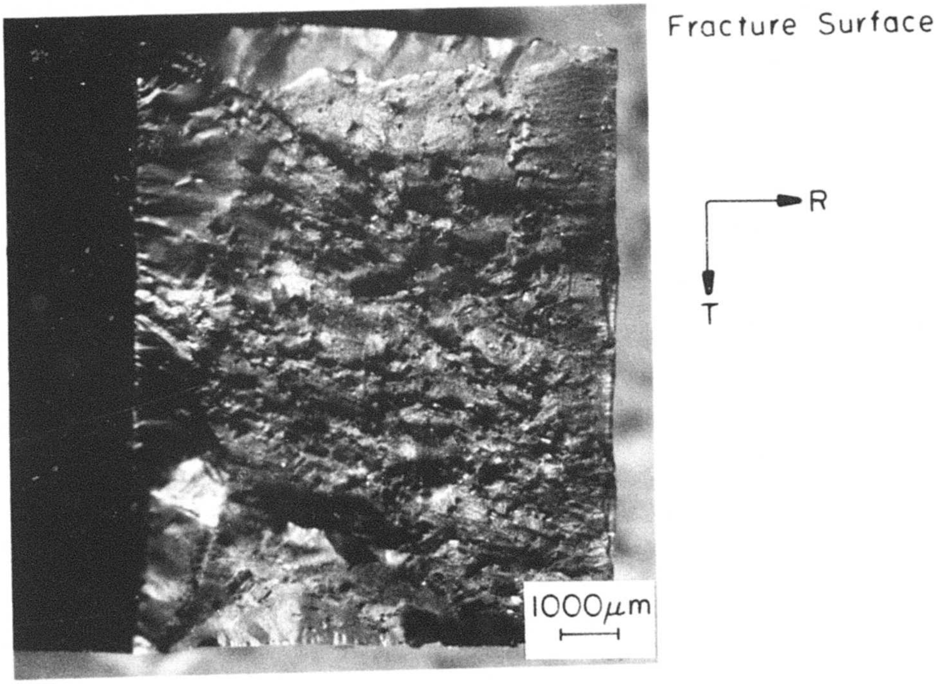


Figure 122 . Alloy 253(10Mo-8V-2.5Al) six inch billet slice, samples 3ELR10 and 3ESR2 (Table XLIV). Solution treated 1275-4 hr WQ, aged 900F-96 hr. Isometric X500, surface replica X5200.

YS(ksi):	172 (L)	RA(%):	31 (L)	K_Q(ksi√in):	78 (LR)
	167 (T)		13 (T)		48 (SR)



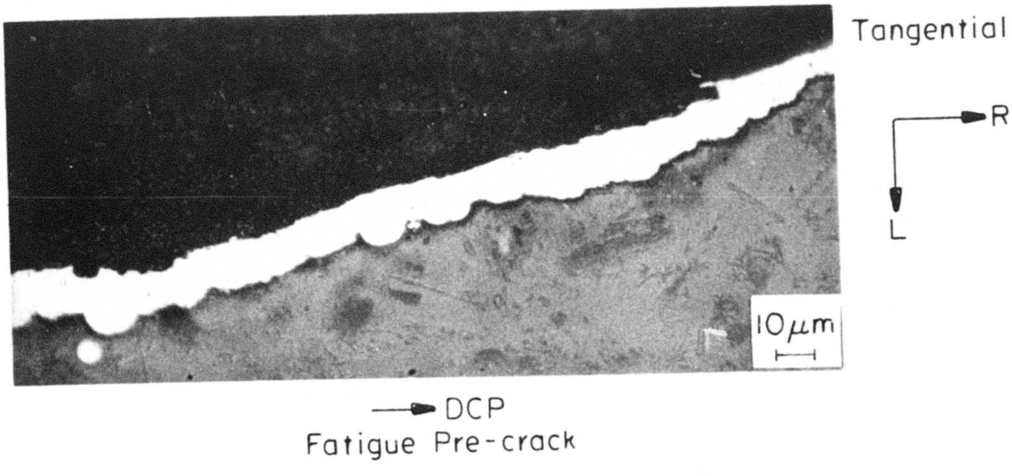


Figure 123 . Alloy 253, sample 3ELR10. Fracture surface X8, crack path X500.

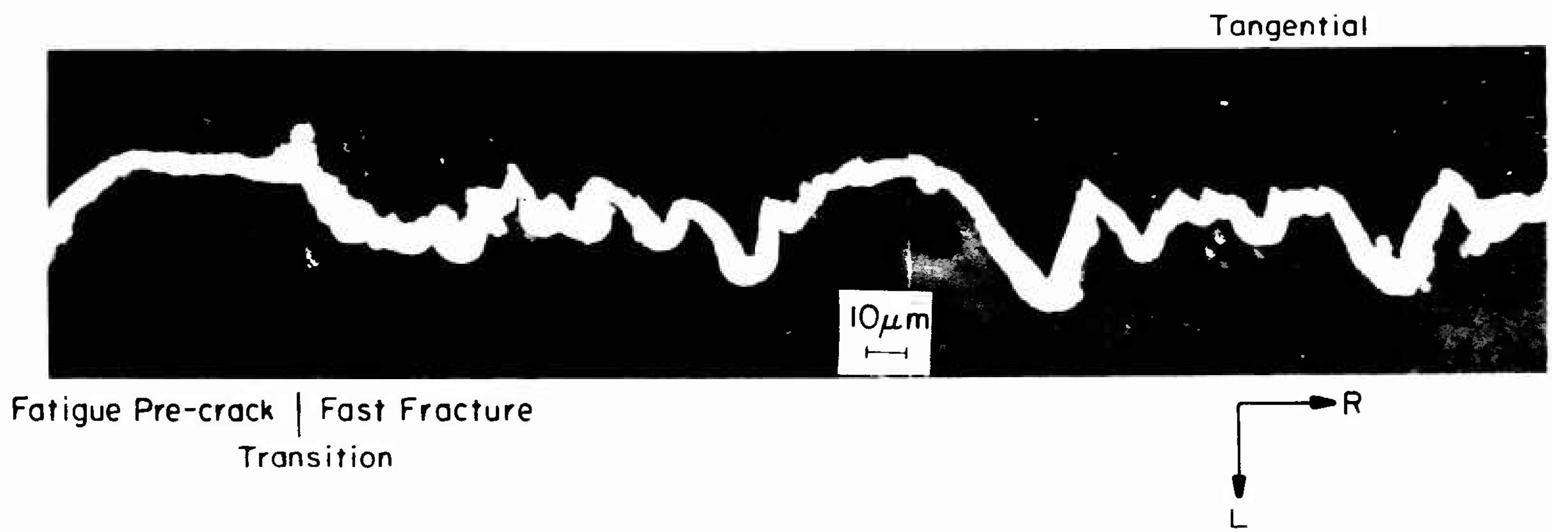


Figure 124 . Alloy 253, sample 3ELR10, X500.

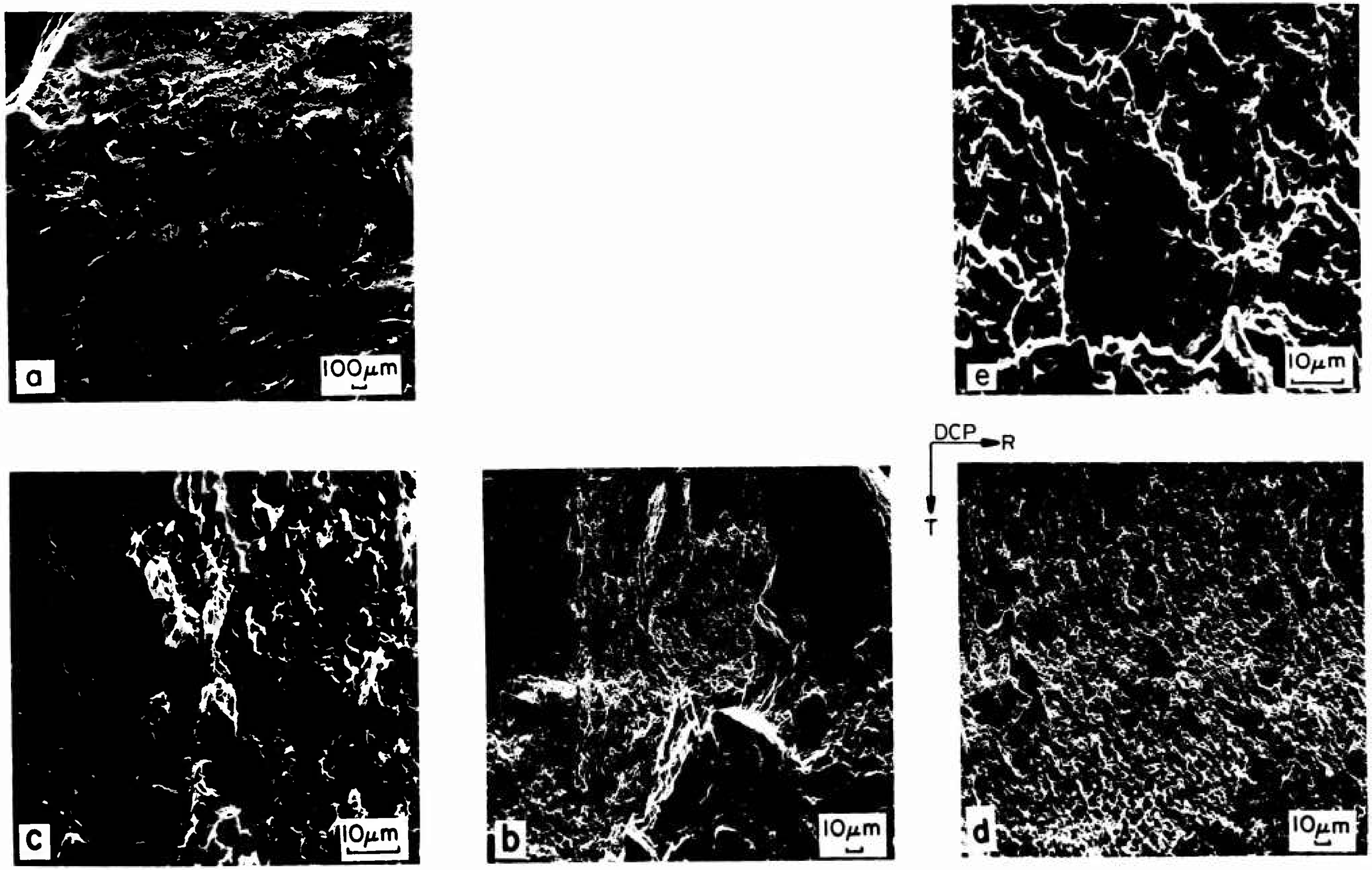
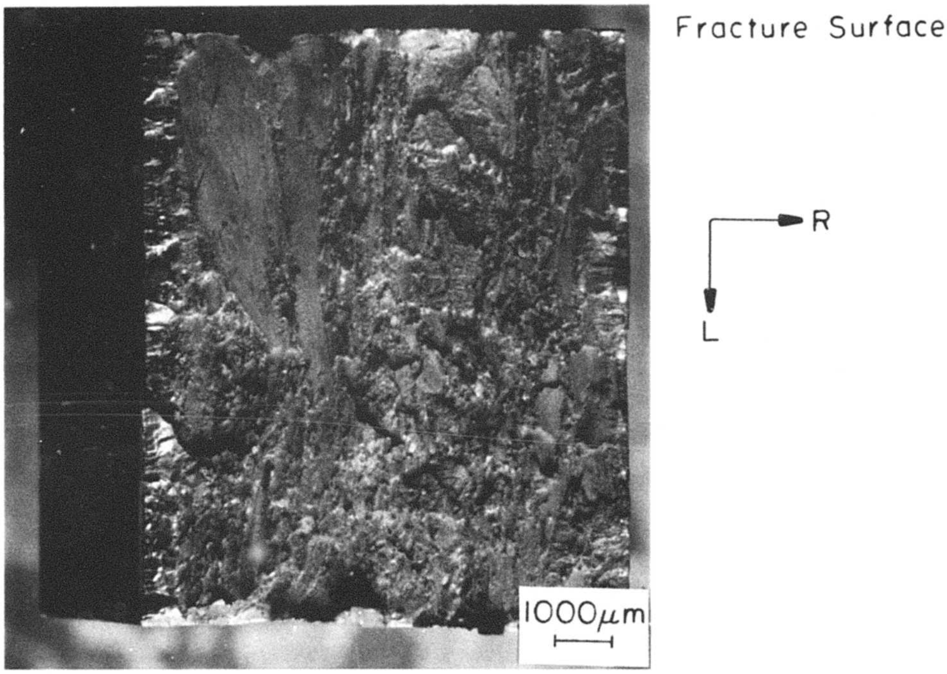


Figure 125 . Alloy 253, sample 3ELR10. SEM of fracture surface (a) X25, (b) X300, (c) X1000-precrack/fast fracture transition, (d) X300, (e) X1000 - fast fracture.



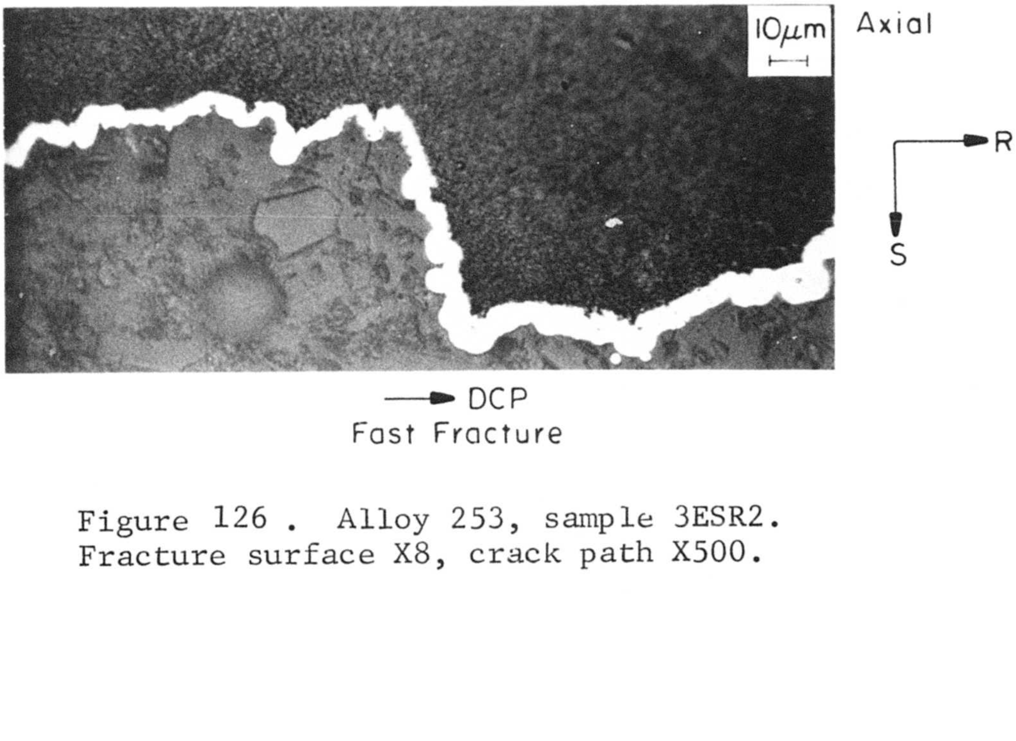


Figure 126 . Alloy 253, sample 3ESR2.
Fracture surface X8, crack path X500.

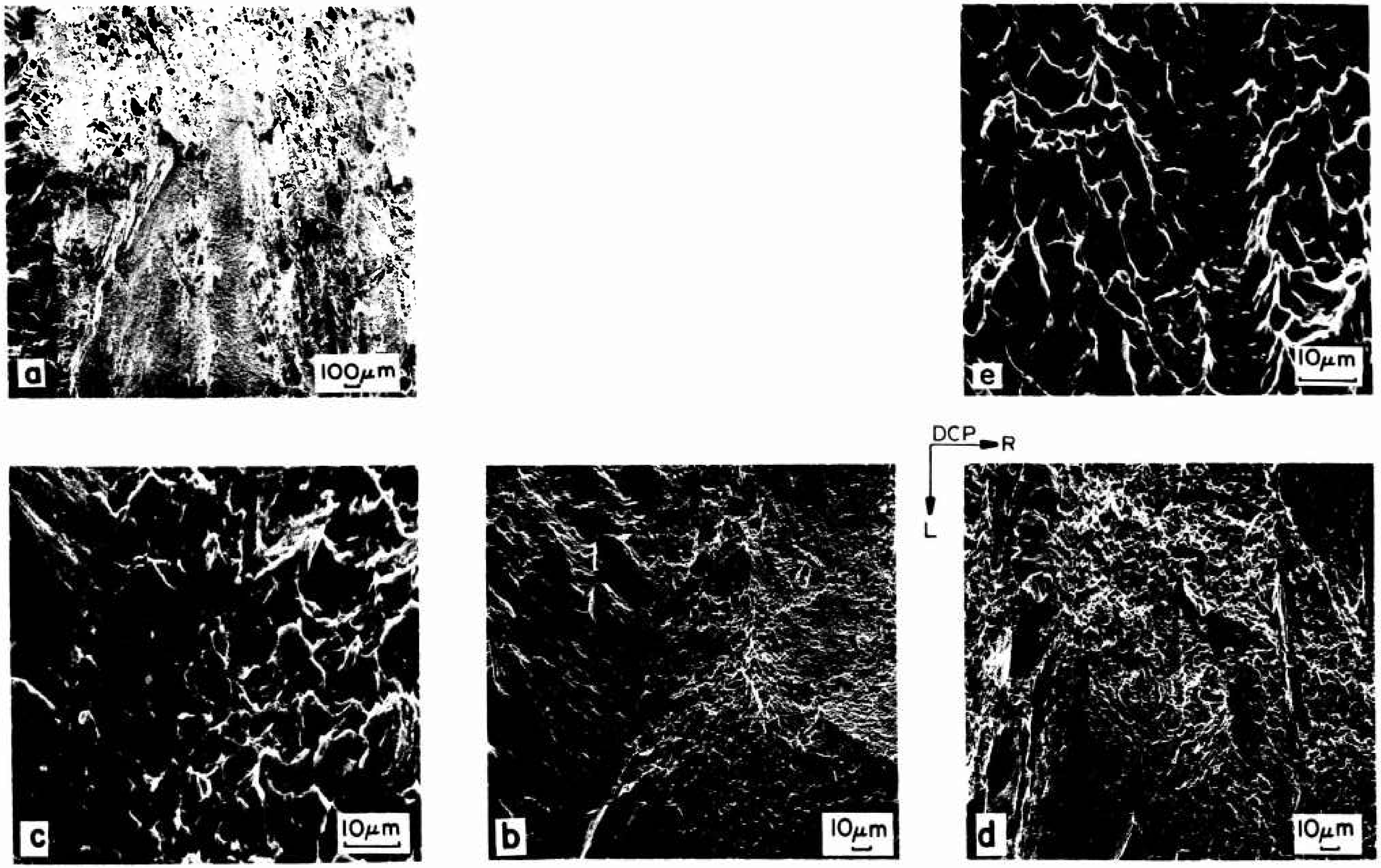


Figure 127 . Alloy 253, sample 3ESR2. SEM of fracture surface (a) X25, (b) X300, (c) X1000-precrack/fast fracture transition, (d) X300, (e) X1000-fast fracture.

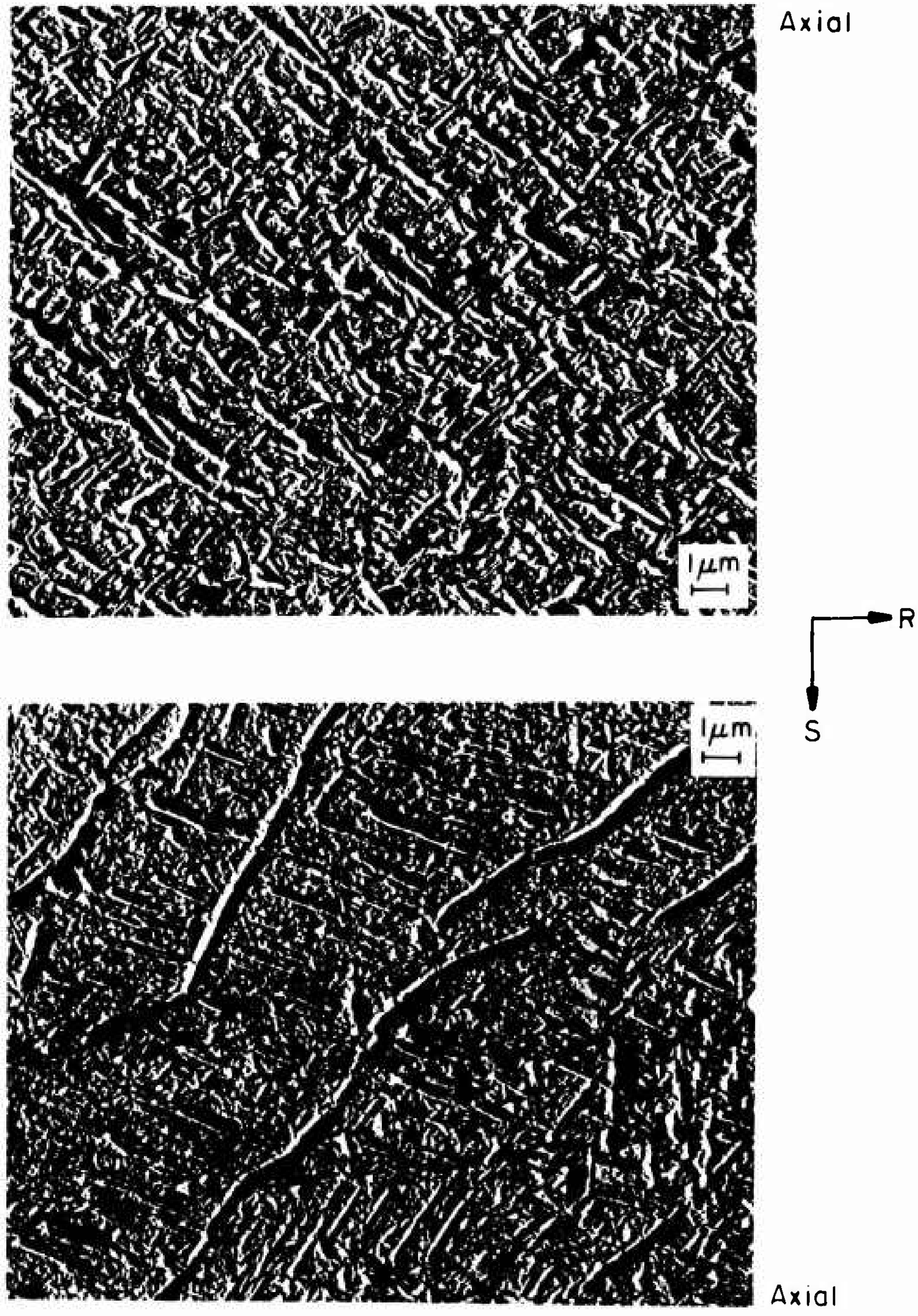


Figure 128 . Alloy 253, sample 3ESR2, (both) surface replicas X5200.

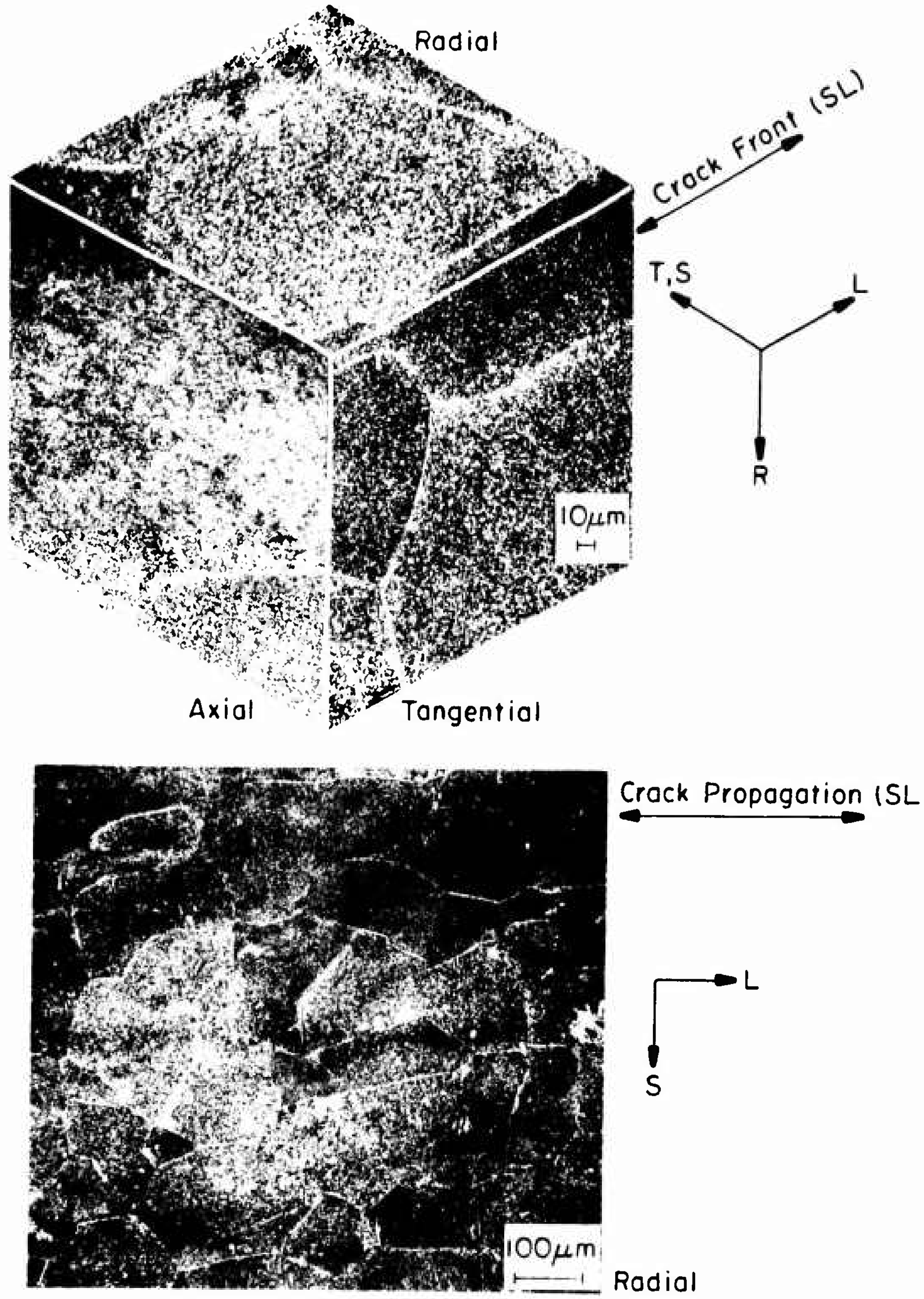


Figure 129 . Alloy 334(10Mo-6Cr-2.5Al) six inch billet slice, sample 4MSL8 (TableLIII). Recrystallize annealed 1525F-1 hr WQ, solution annealed 1300F-4 hr WQ, aged 900F-96 hr. Isometric X250, radial face X100.

YS(ksi):	167 (L)	RA(%):	14 (L)	K_Q(ksi$\sqrt{in}$):	58 (LR)
	178 (T)		6 (T)		45 (SL)

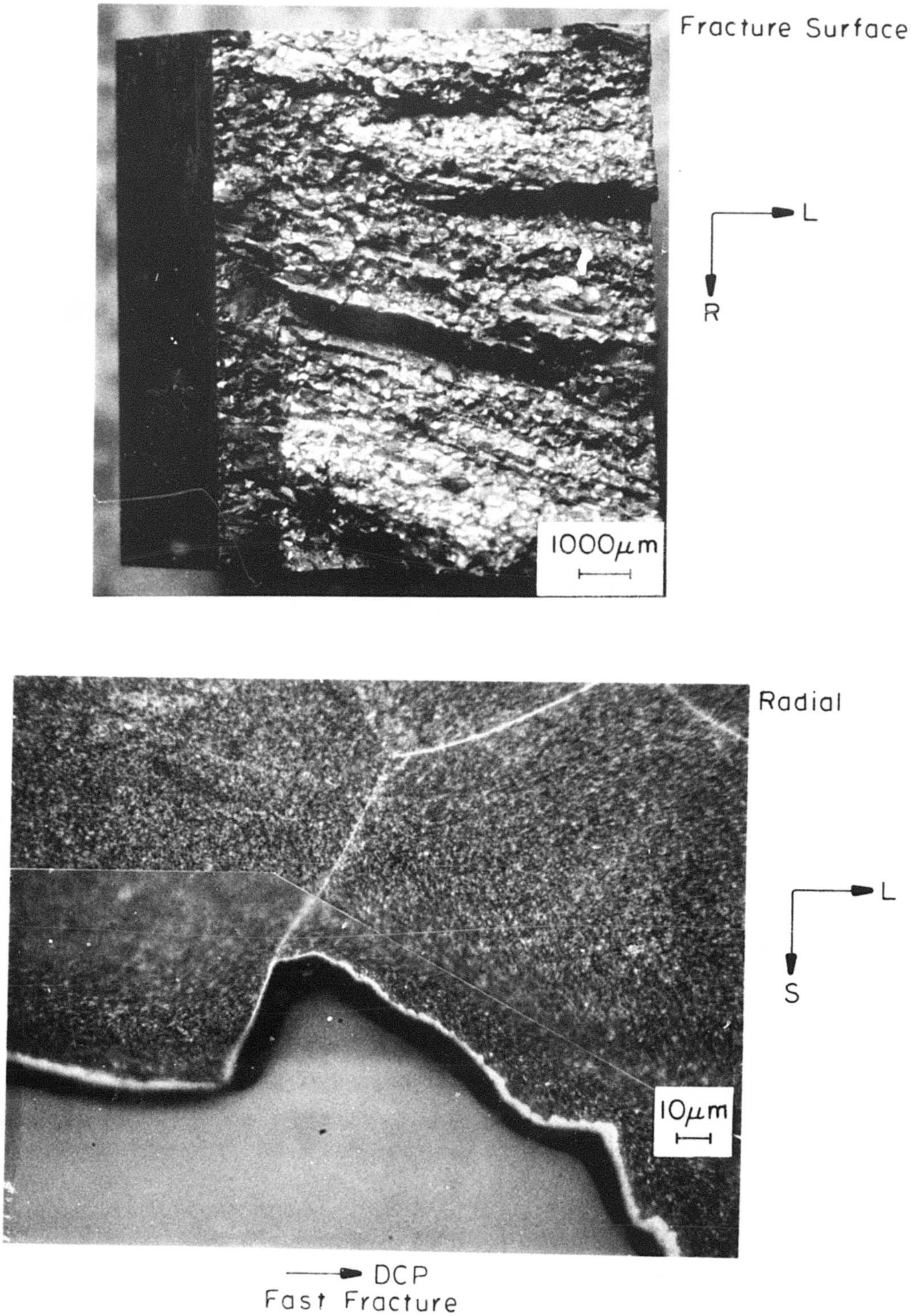


Figure 130. Alloy 334, sample 4MSL8. Fracture surface X8, crack path X500. Note faceted appearance of fracture surface, mixed mode transgranular/intergranular crack propagation.

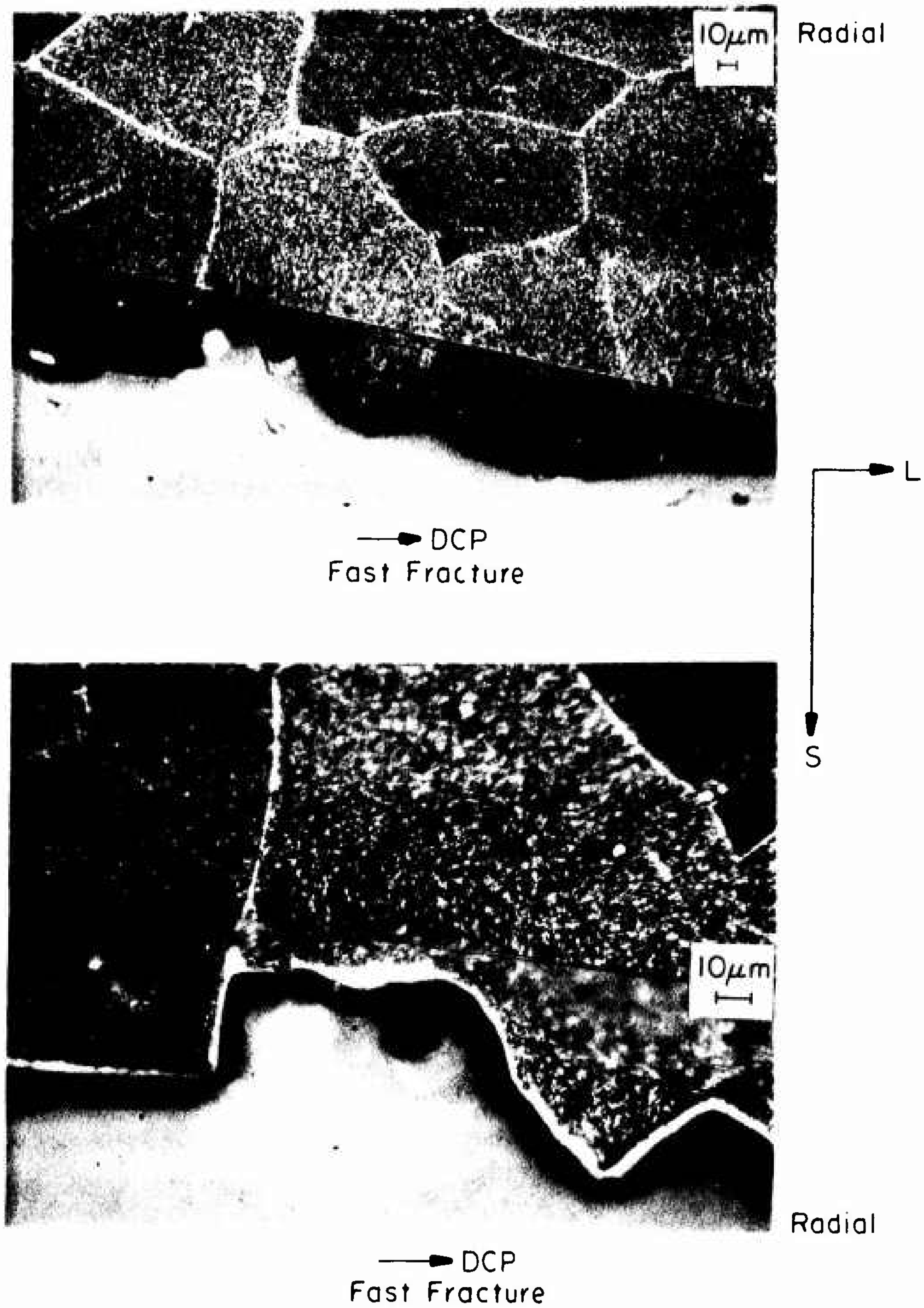


Figure 131 . Alloy 334, sample 4MSL8. Crack path (top) X250, (bottom) X500. Mixed mode transgranular/intergranular crack propagation.

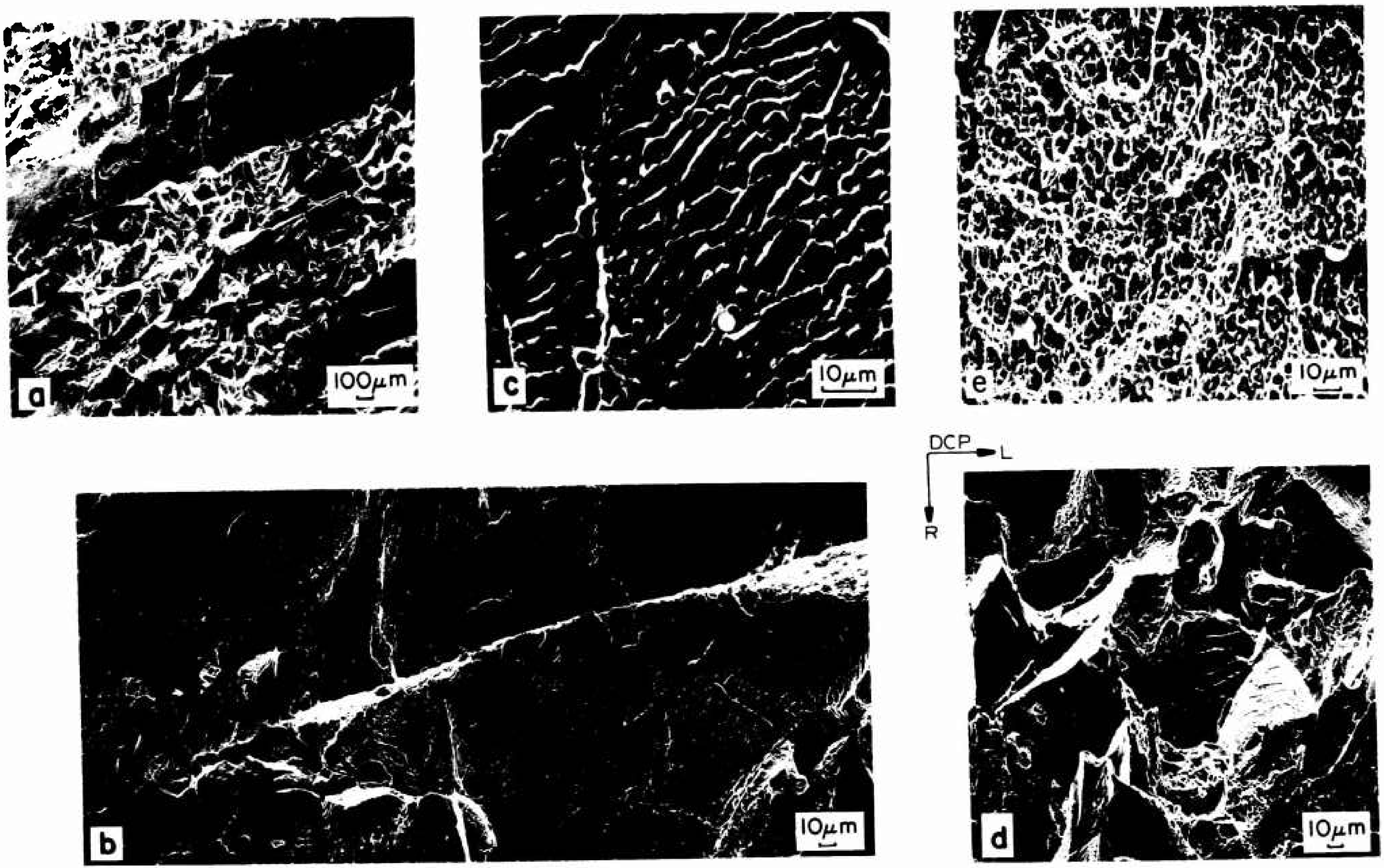


Figure 132. Alloy 334, sample 4MSL8. SEM of fracture surface (a) X30, (b) X300-precrack/fast fracture transition, (c) X1000-fast fracture close to transition, (d) X250, (e) X500-fast fracture

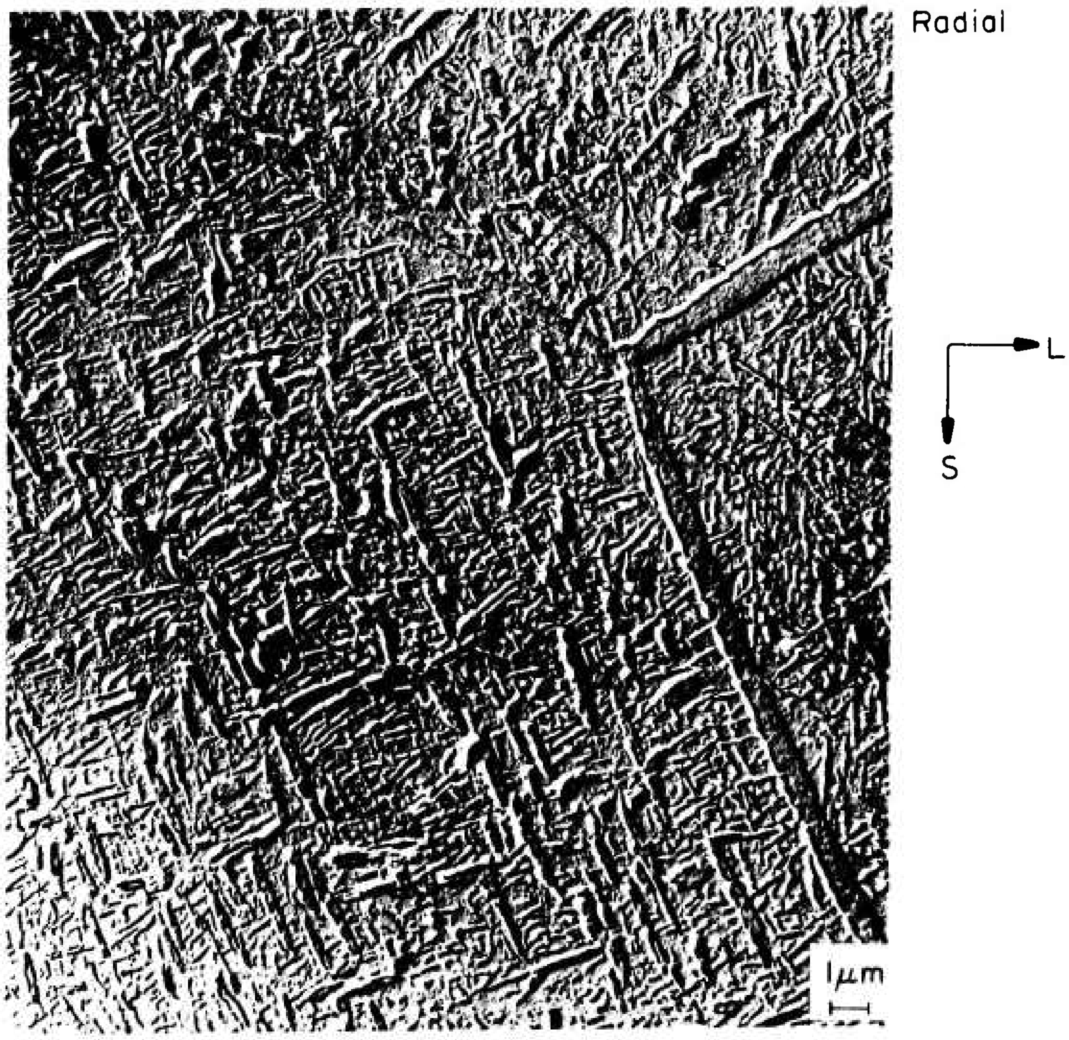
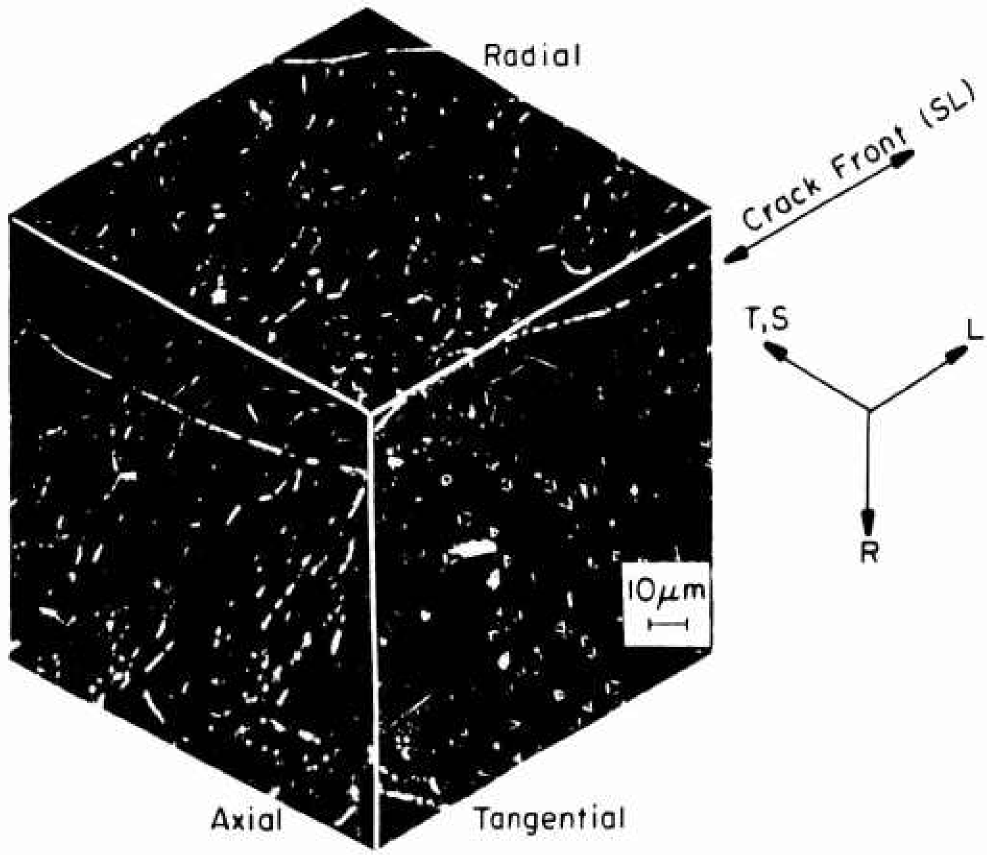


Figure 133 . Alloy 334, sample 4MSL8, surface replica X5200. Note continuous grain boundary alpha.



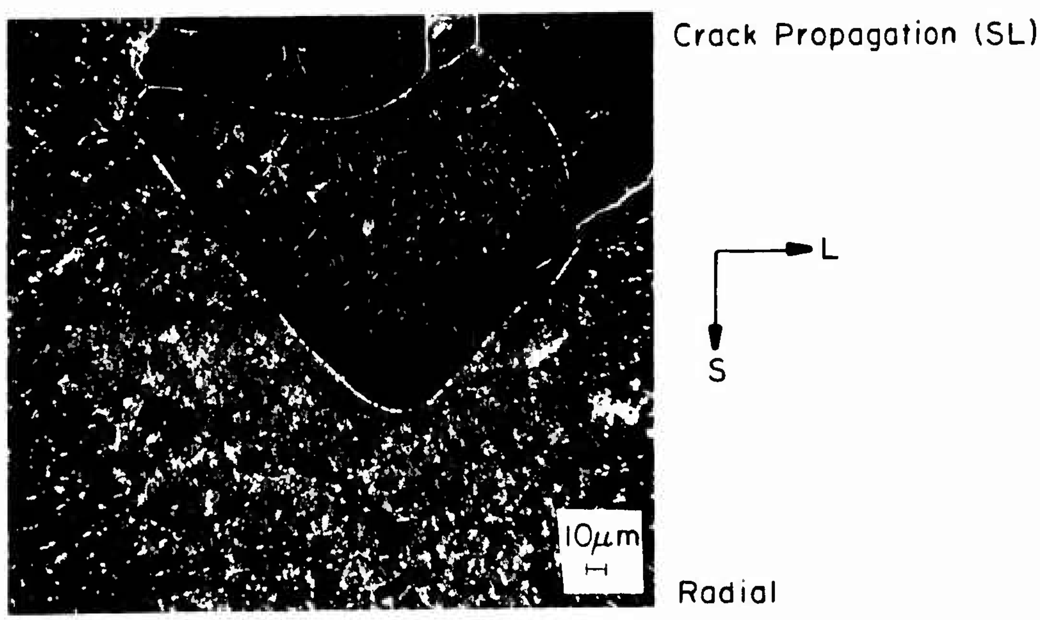


Figure 134. Alloy 227(7Mo-4Cr-2.5Al). Six inch slice, sample 7MSL4 (Table LIV). Recrystallize annealed 1575F-½ hr Wq, solution annealed 1475F-2 hr WQ, aged 1025F-8 hr. Isometric X500, radial face X250.

YS(ksi):	180 (L)	RA(%):	5 (L)	K_Q(ksi√in):	57 (LR)
	188 (T)		6 (T)		41 (SL)

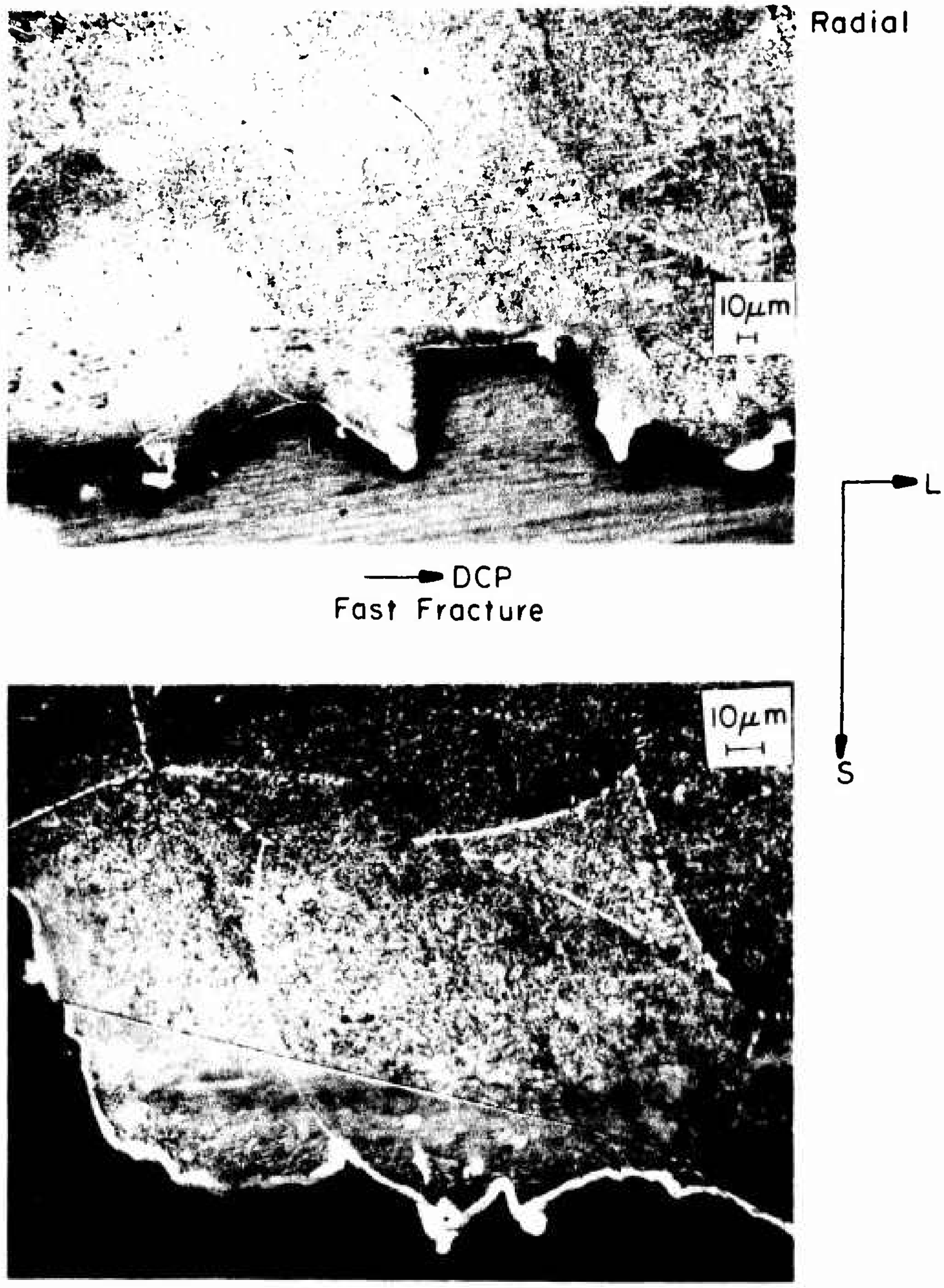


Figure 135 . Alloy 227, sample 7MSL4. Crack path (top) X250, (bottom) X500. Mixed mode transgranular/intergranular crack propagation.

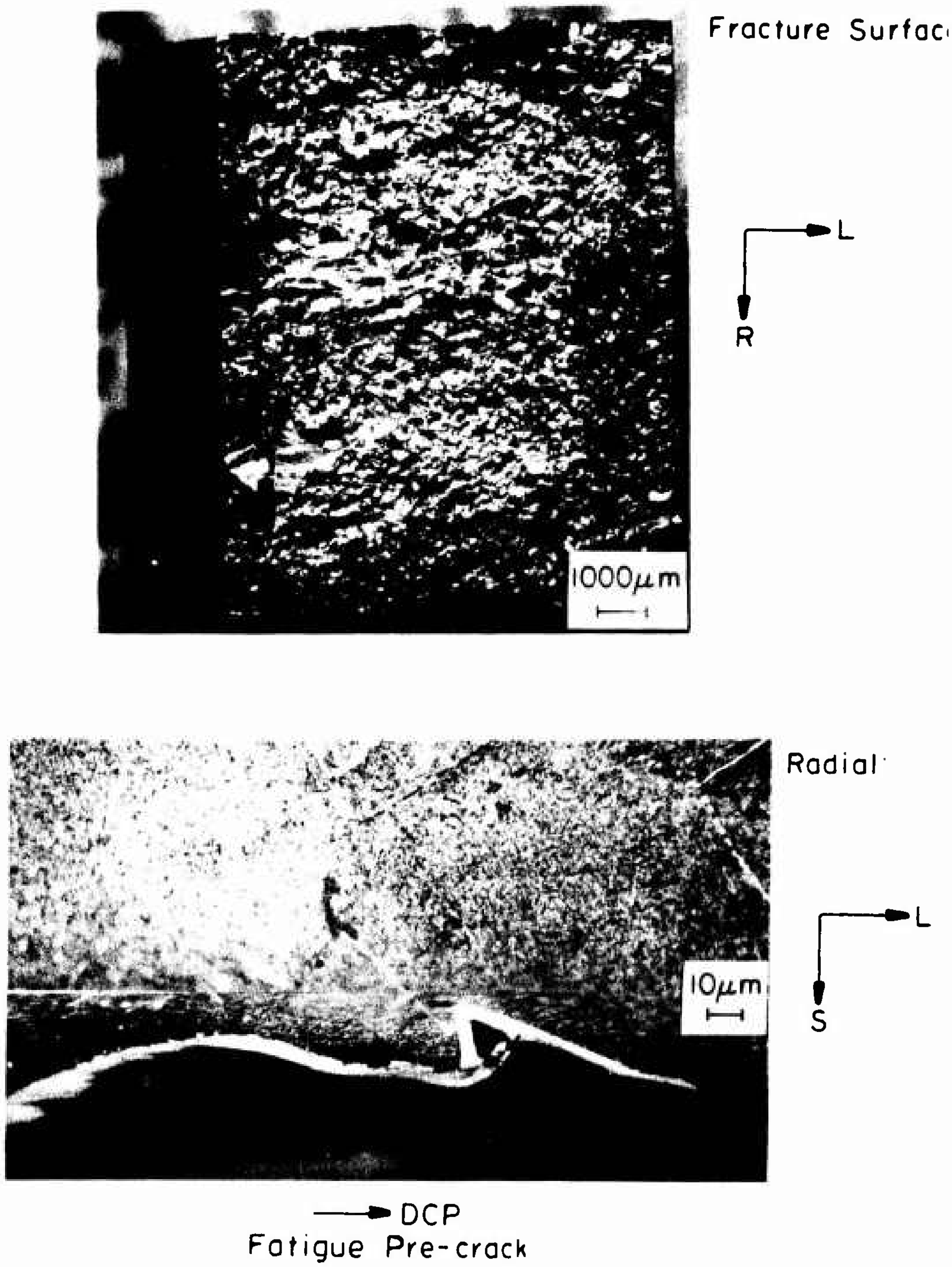


Figure 136 . Alloy 227, sample 7MSL4. Fracture surface X8, crack path X500. Note faceted appearance of fracture surface; essentially flat crack path with some tendency to follow continuous grain boundary alpha.

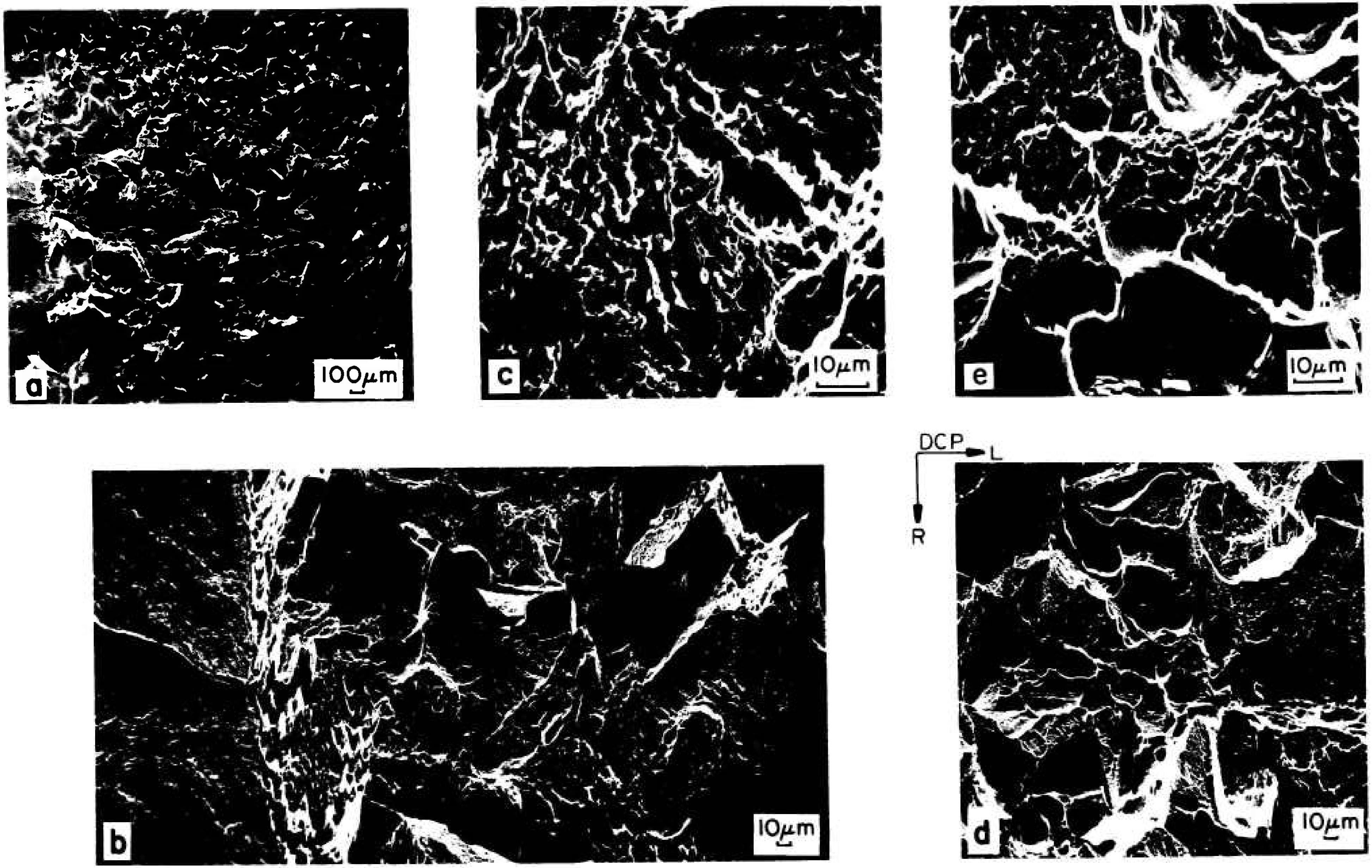


Figure 137. Alloy 227, sample 7MSL4. SEM of fracture surface (a) X25, (b) X250 - precrack/ fast fracture transition, (c) X900 - fast fracture close to transition, (d) X250, (e) X900 - fast fracture.

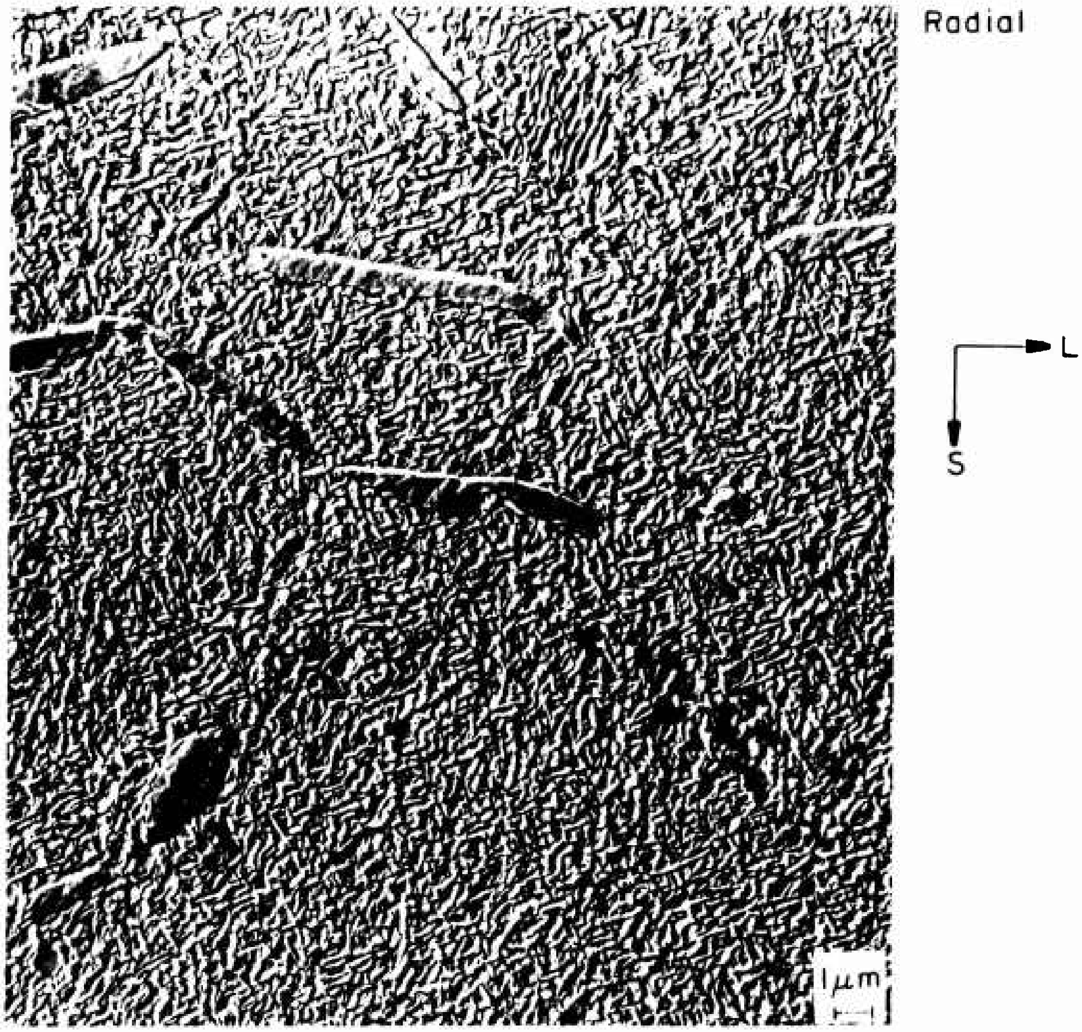


Figure 138. Alloy 227, sample 7MSL4, surface replica X5200.

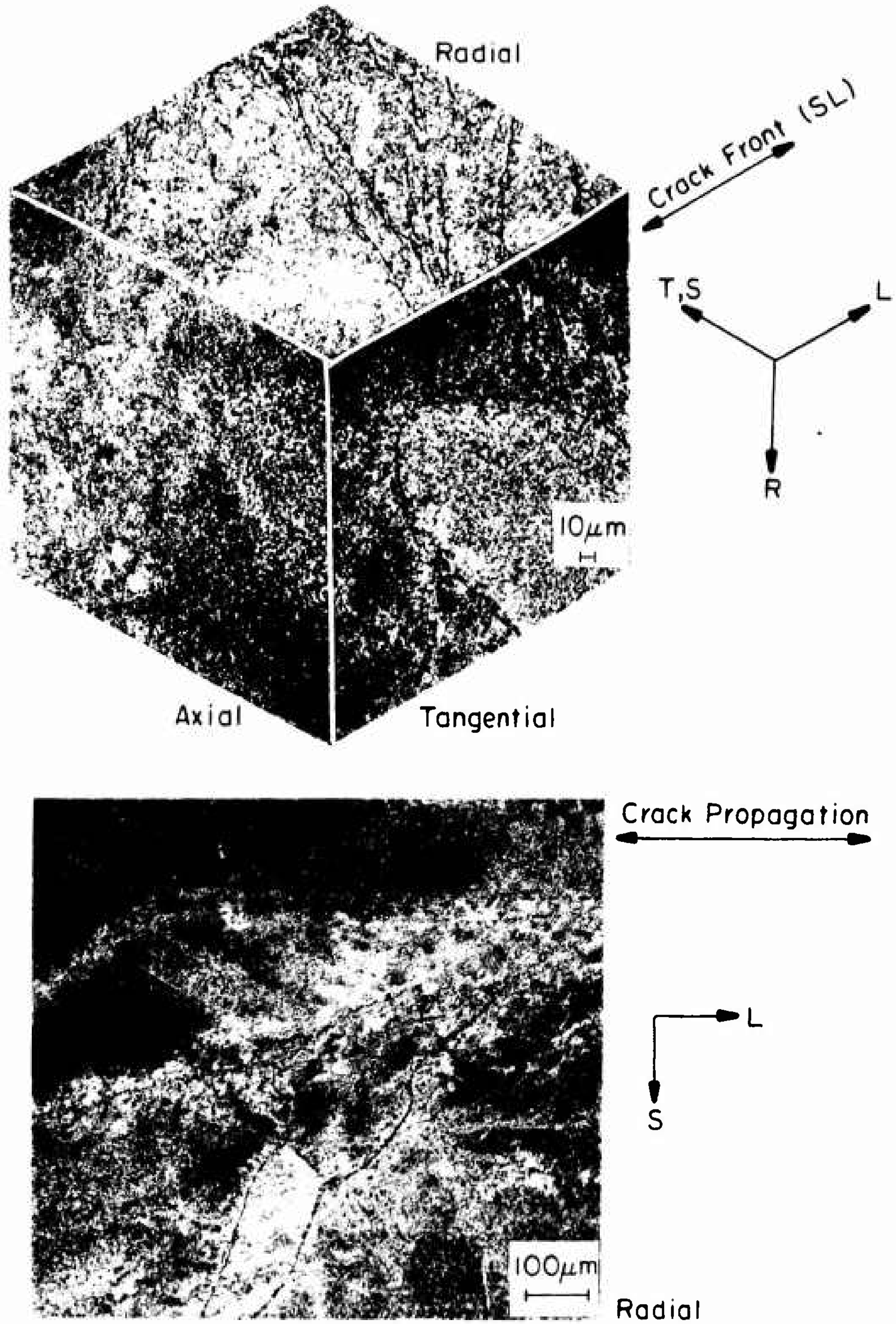


Figure 139 . Alloy 334(10Mo-6Cr-2.5Al). 10.5 inch RCS slice, sample 4SL2 (Table L). Solution annealed 1300F-4 hr WQ, aged 900F-96 hr. Isometric X250, radial face X100.

YS(ksi):	177 (L)	RA(%):	13 (L)	K (ksi√in):	99 (LR)
	182 (T)		9 (T)		60 (SL)

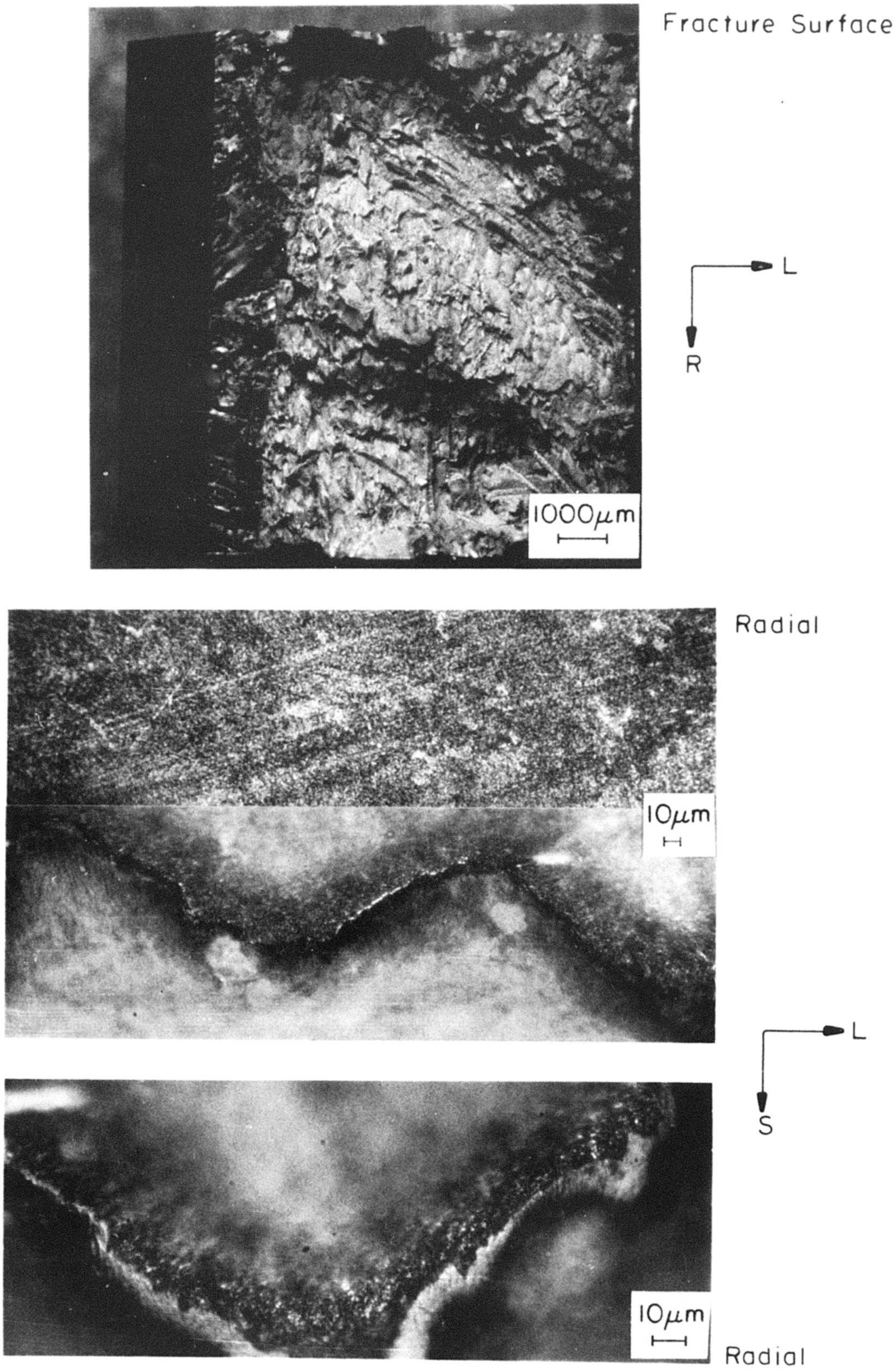


Figure 140. Alloy 334, sample 4SL2. Fracture surface X8, crack path (top) X250, (bottom) X500.

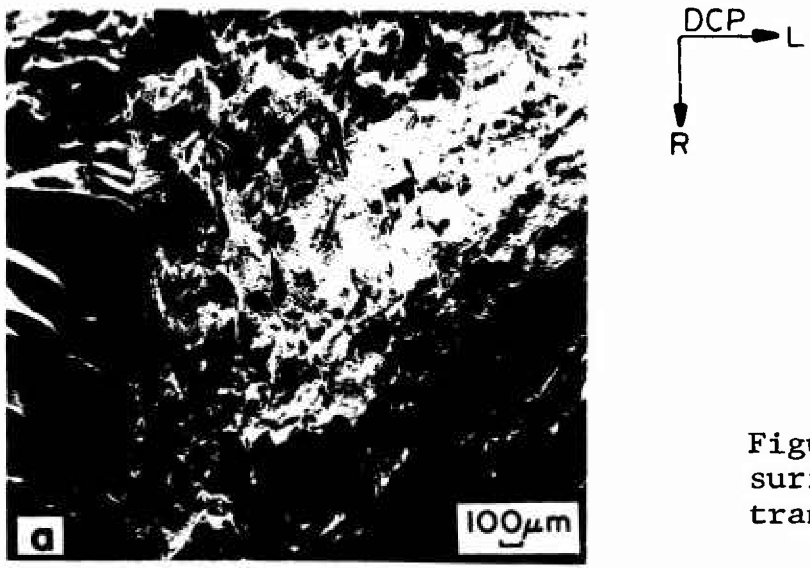
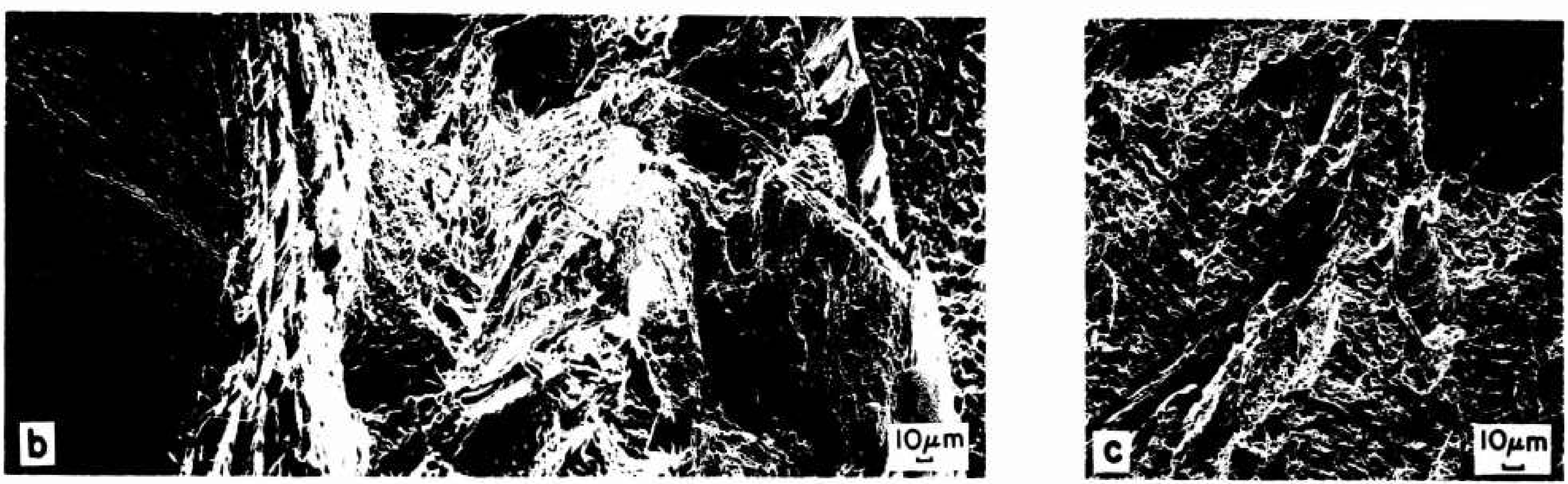


Figure 141. Alloy 334, sample 4SL2. SEM of fracture surface (a) X30, (b) X200 - precrack/fast fracture transition, (c) X300 - fast fracture.



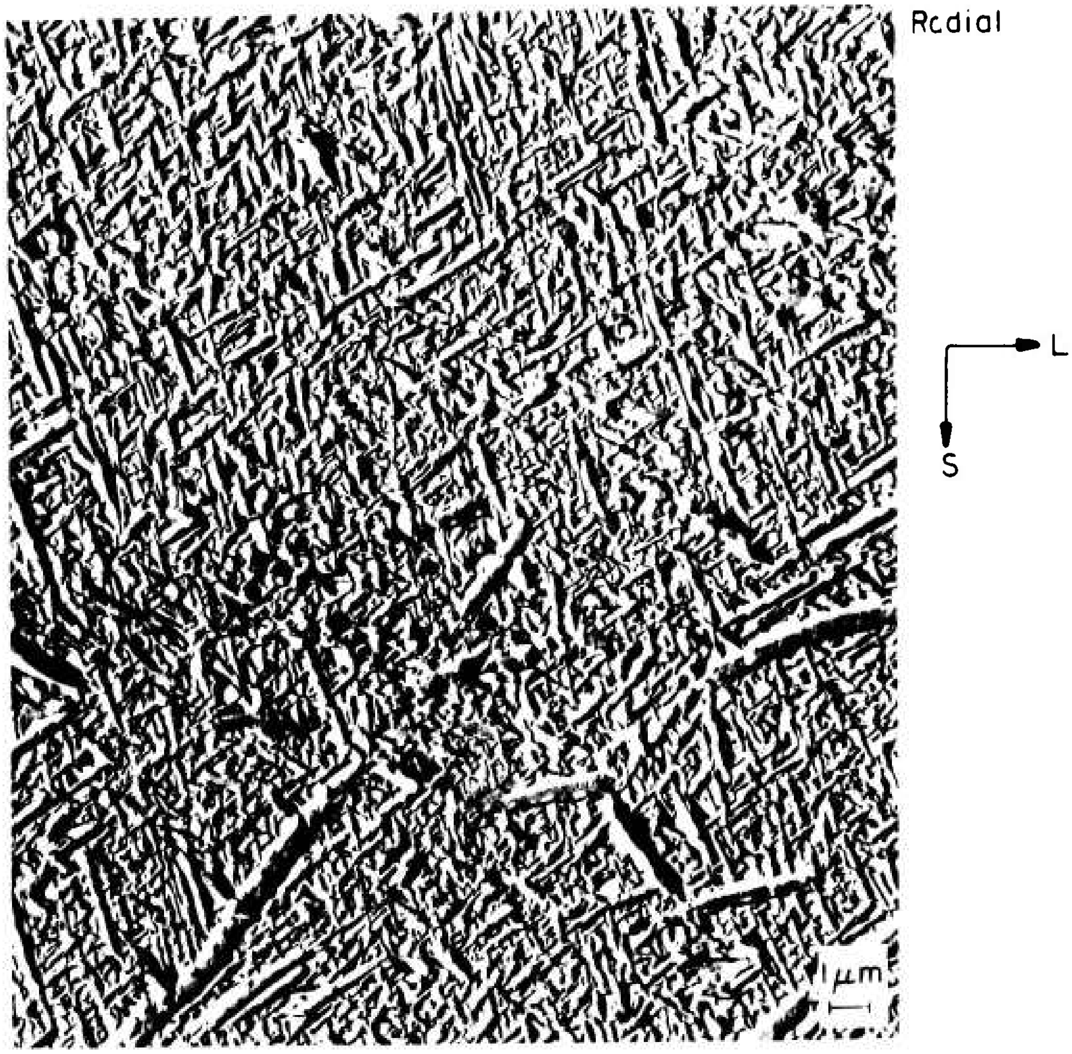


Figure 142. Alloy 334, sample 4SL2. Surface replica X5200.

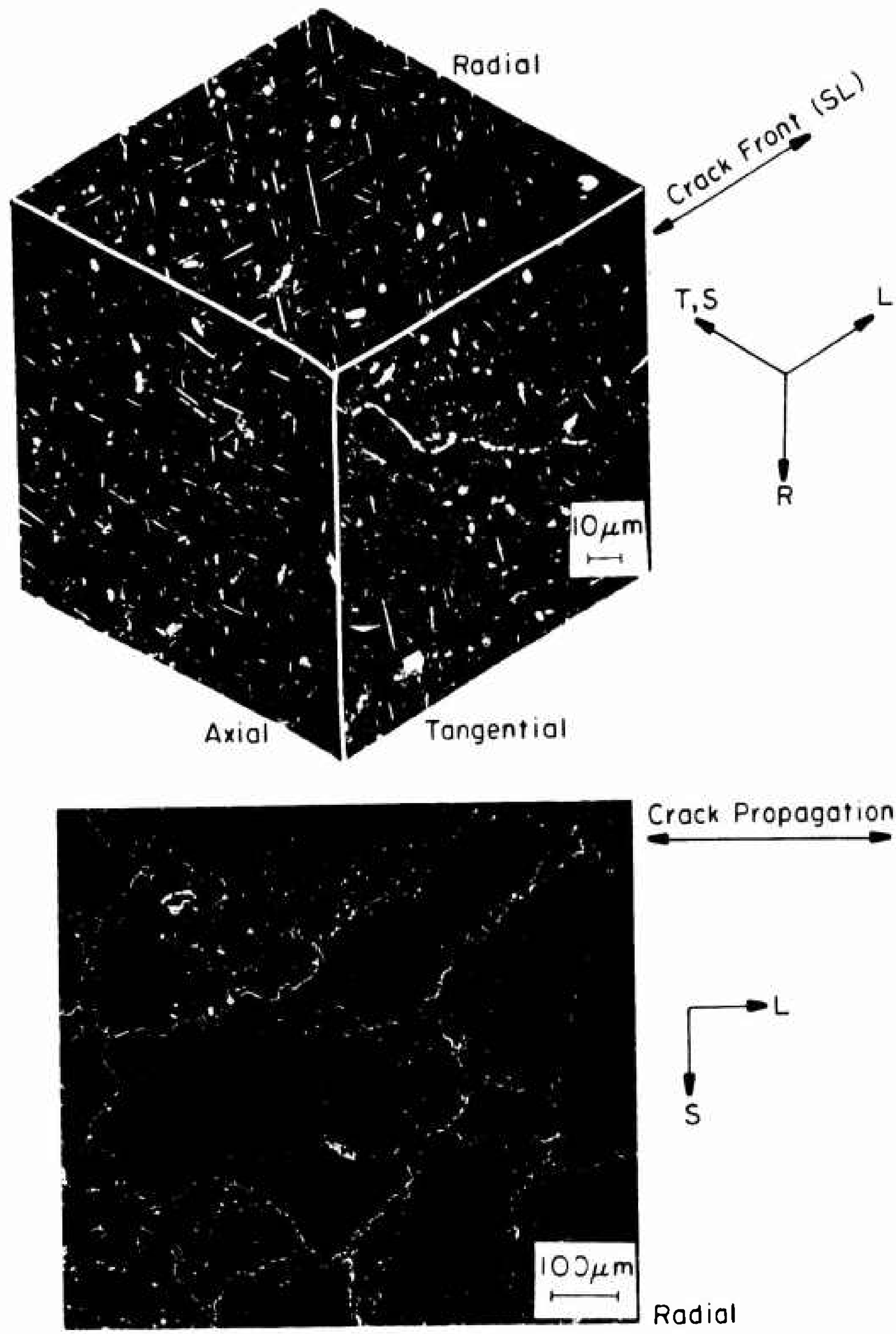


Figure 143. Alloy 227(7Mo-4Cr-2.5Al). 10.5 inch RCS slice, sample 7SL2 (Table LI). Solution annealed 1475F - 2 hr WQ, aged 1025F - 8 hr. Isometric X500, radial face X100.

YS(ksi):	183 (L)	RA(%):	13 (L)	K_Q(ksi$\sqrt{in}$):	53 (LR)
	184 (T)		10 (T)		57 (SL)

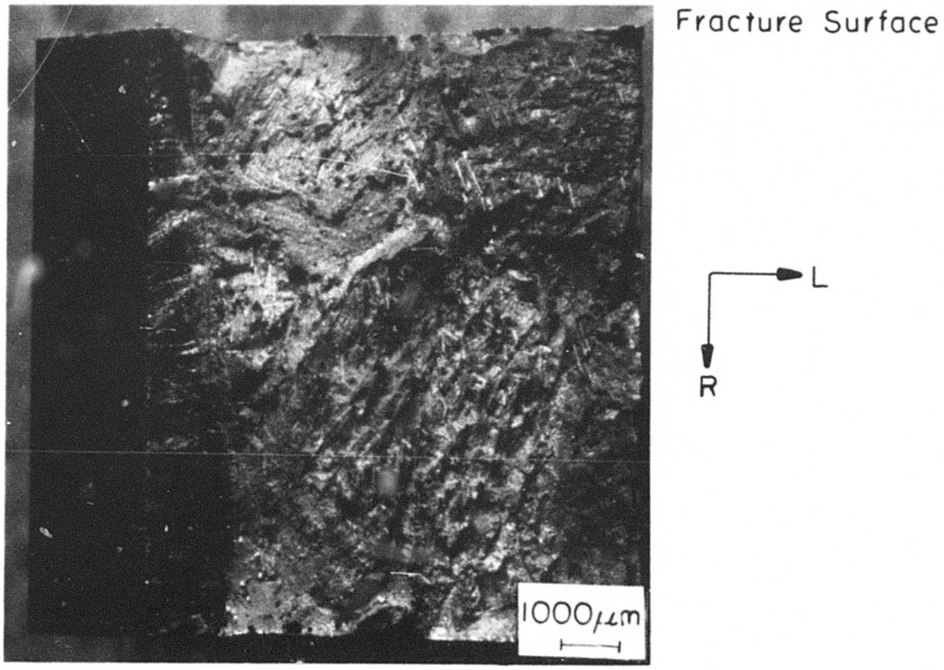


Figure 144 . Alloy 227, sample 7SL2. Fracture surface X8.

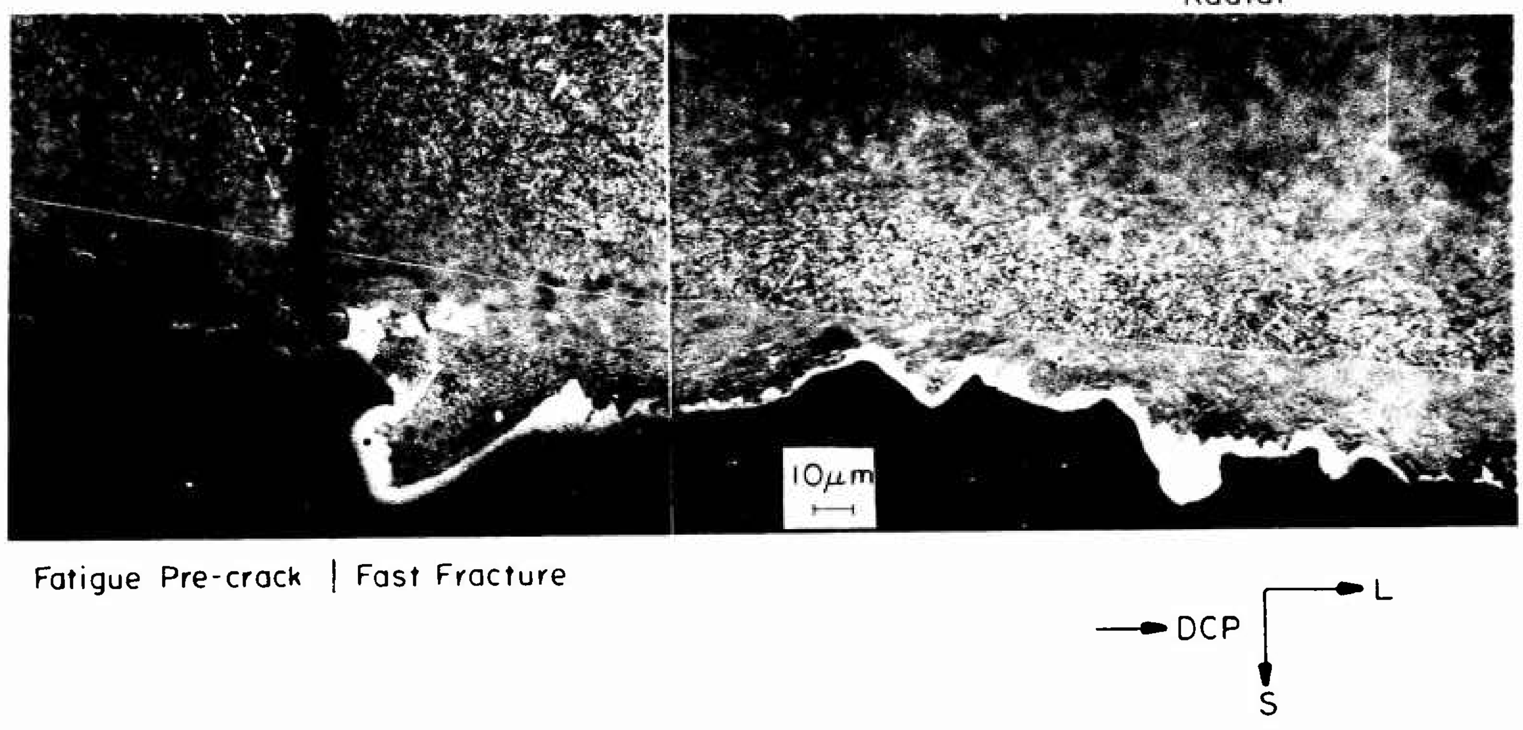


Figure 145. Alloy 227, sample 7SL2, X500.

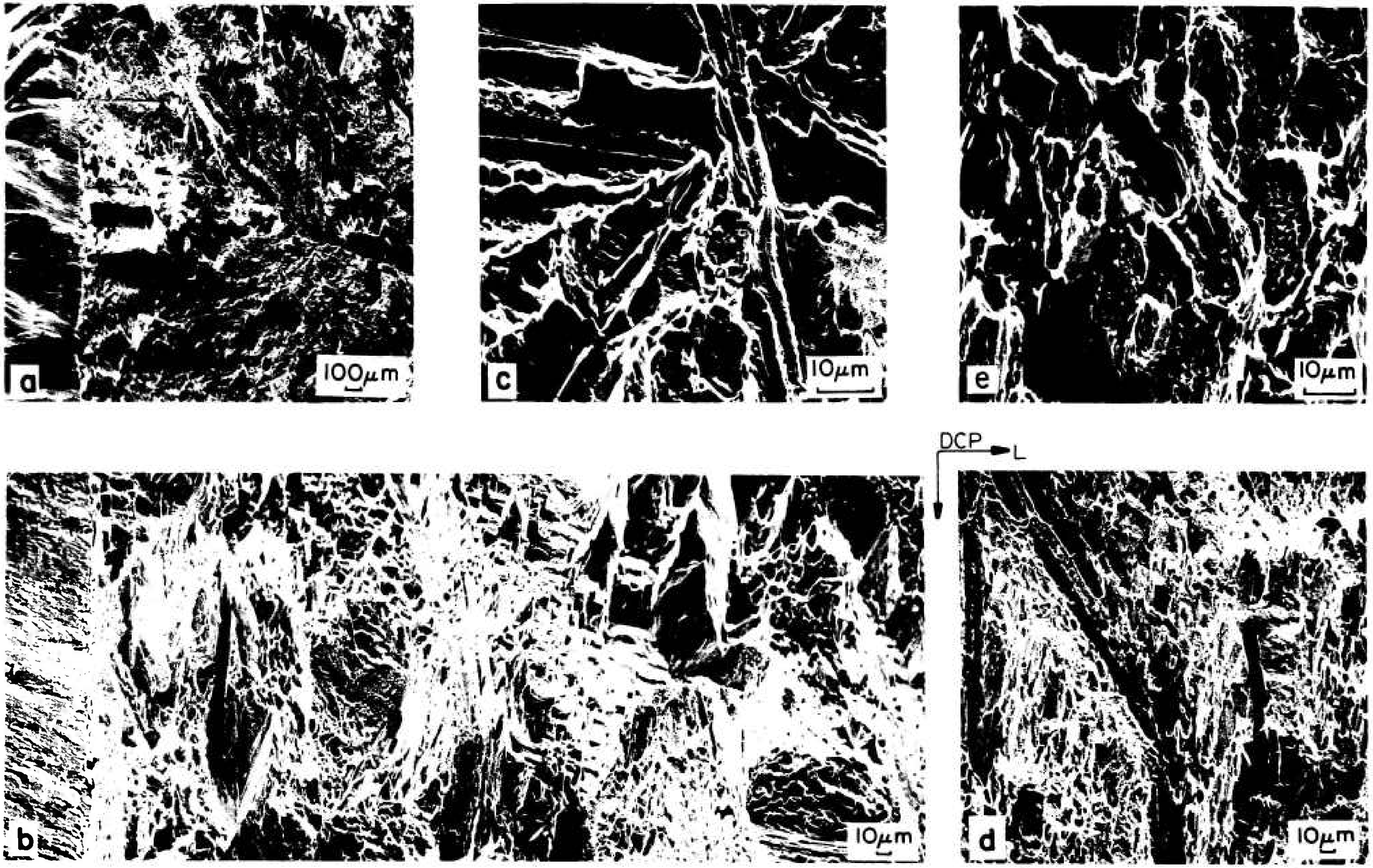


Figure 146. Alloy 227, sample 7SL2. SEM of fracture surface (a) X30, (b) X250 - precrack/fast fracture transition, (c) X1000 - fast fracture close to transition, (d) X250, (e) X1000 - fast fracture.

Figure 147. Alloy 227, sample 7SL2, surface replica X5200.

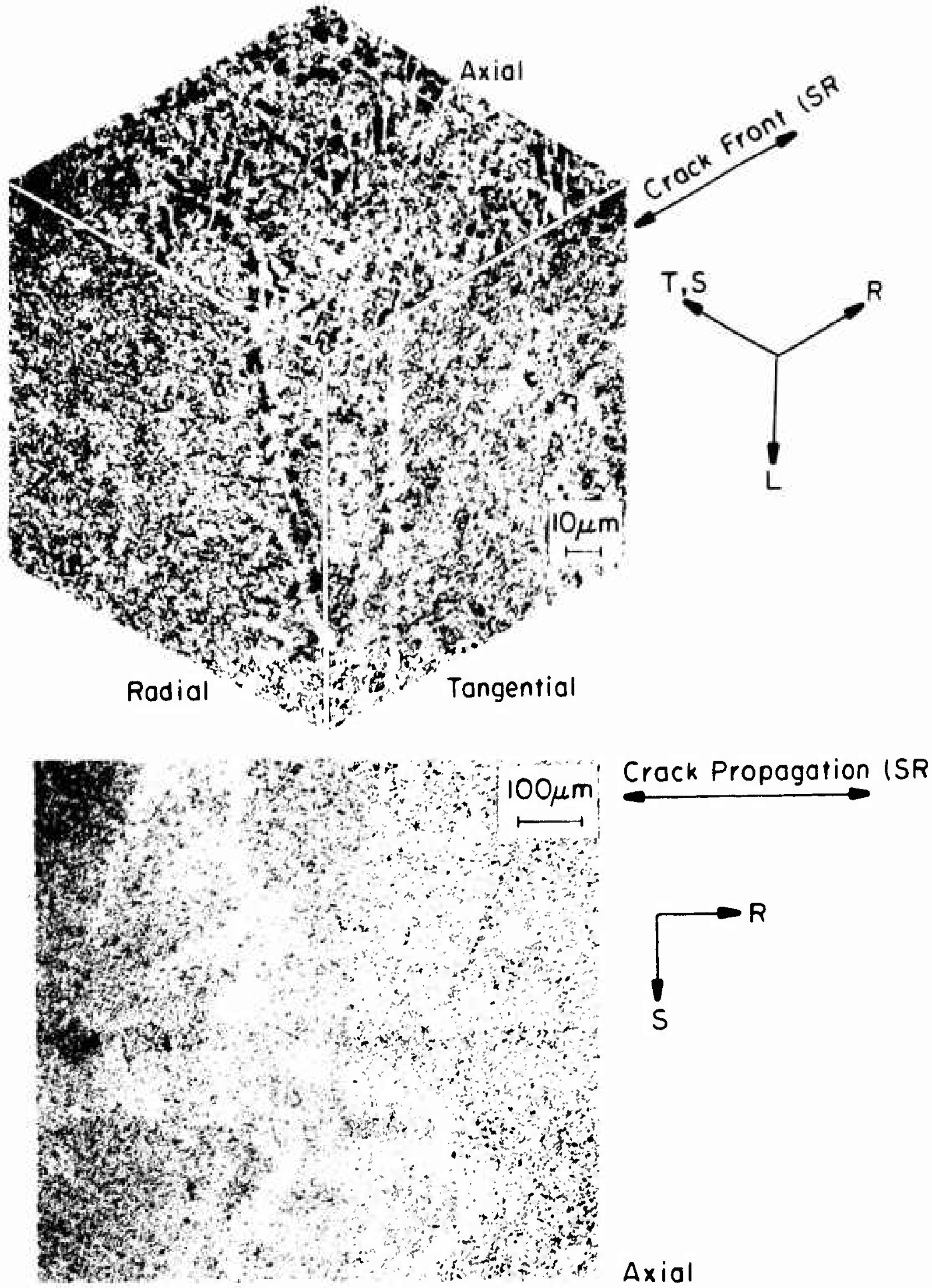
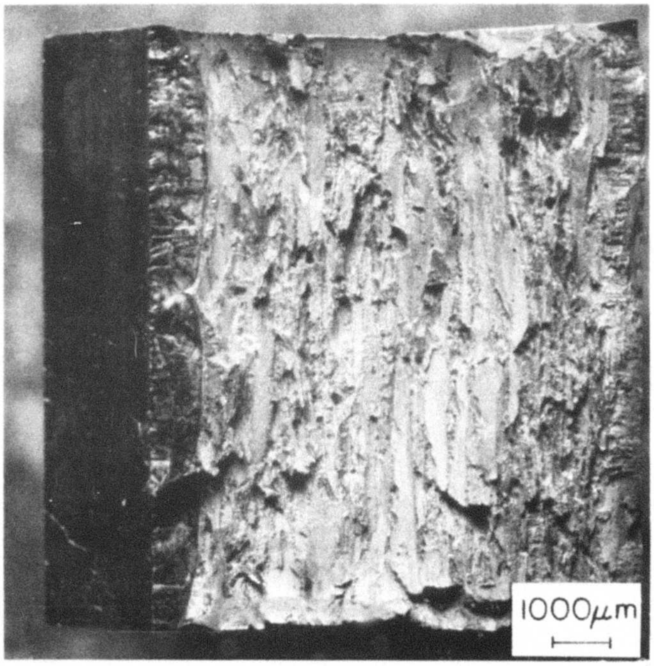


Figure 148 . Alloy 334(10Mo-6Cr-2.5Al). Six inch billet slice, sample 4SR12 (Table LX). Solution annealed 1350F - 4 hr WQ plus 1200F - 4 hr WQ, aged 900F - 96 hr. Isometric X500, axial face X100.

YS(ksi):	147 (L)	RA(%):	39 (L)	K_Q(ksi/in):	158 (LR)
	149 (T)		23 (T)		83 (SR)



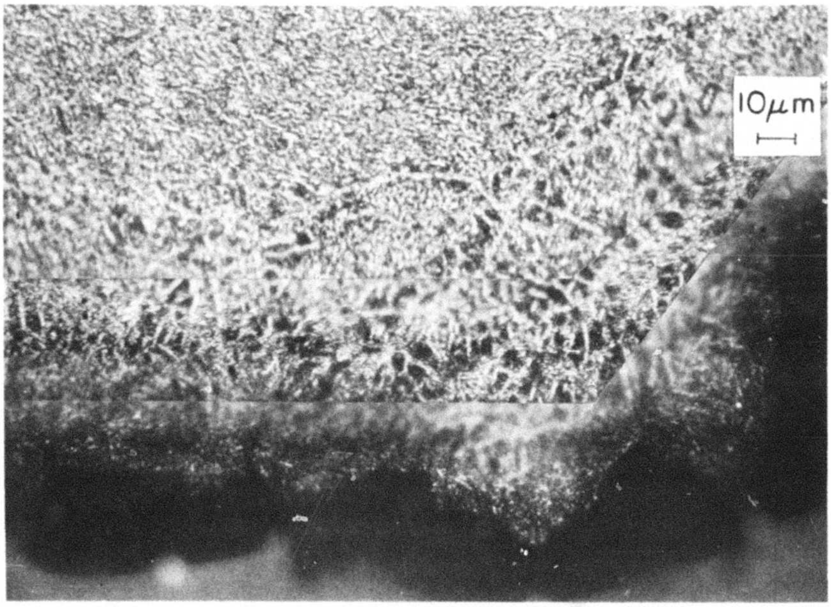


Figure 149 . Alloy 334, sample 4SR12. Fracture surface X8, crack path X500.

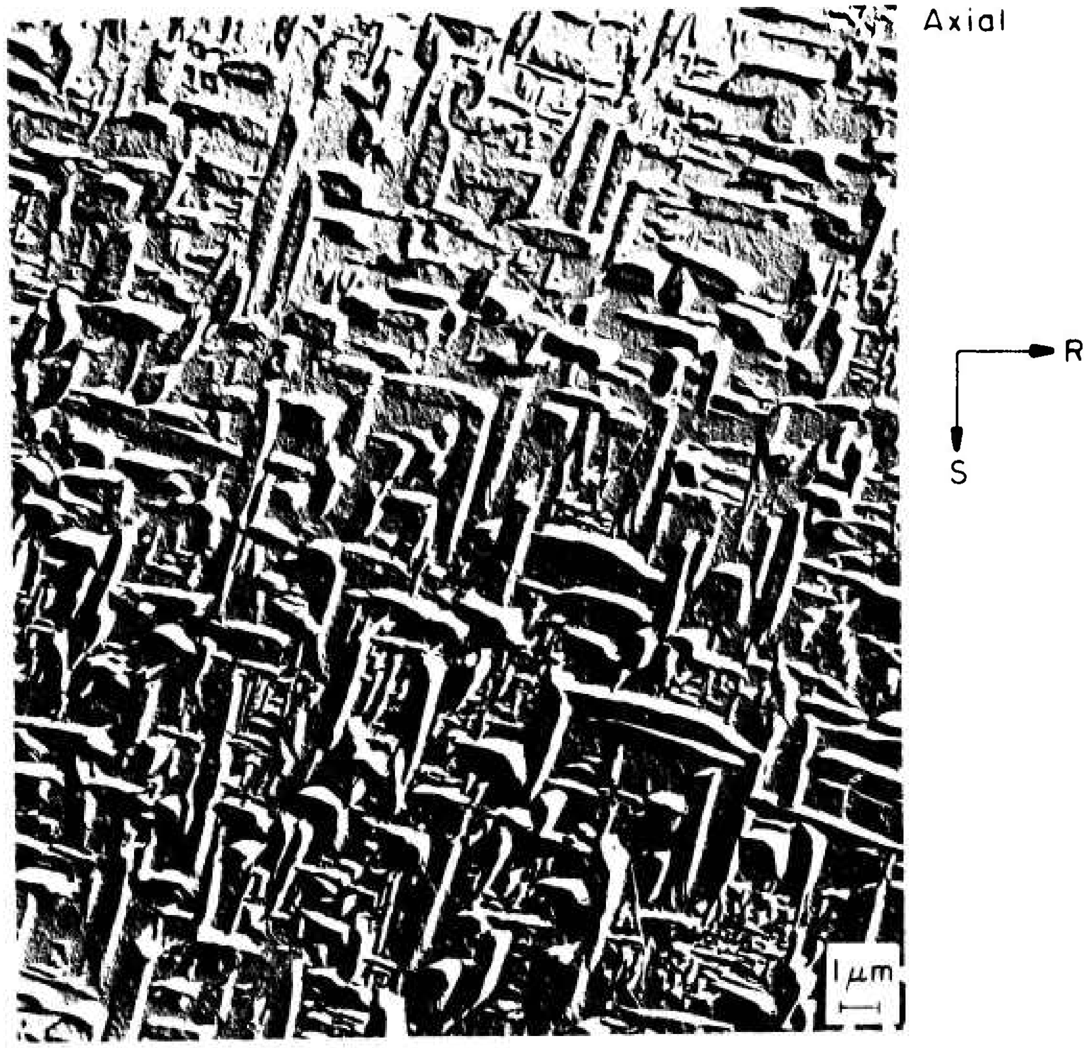
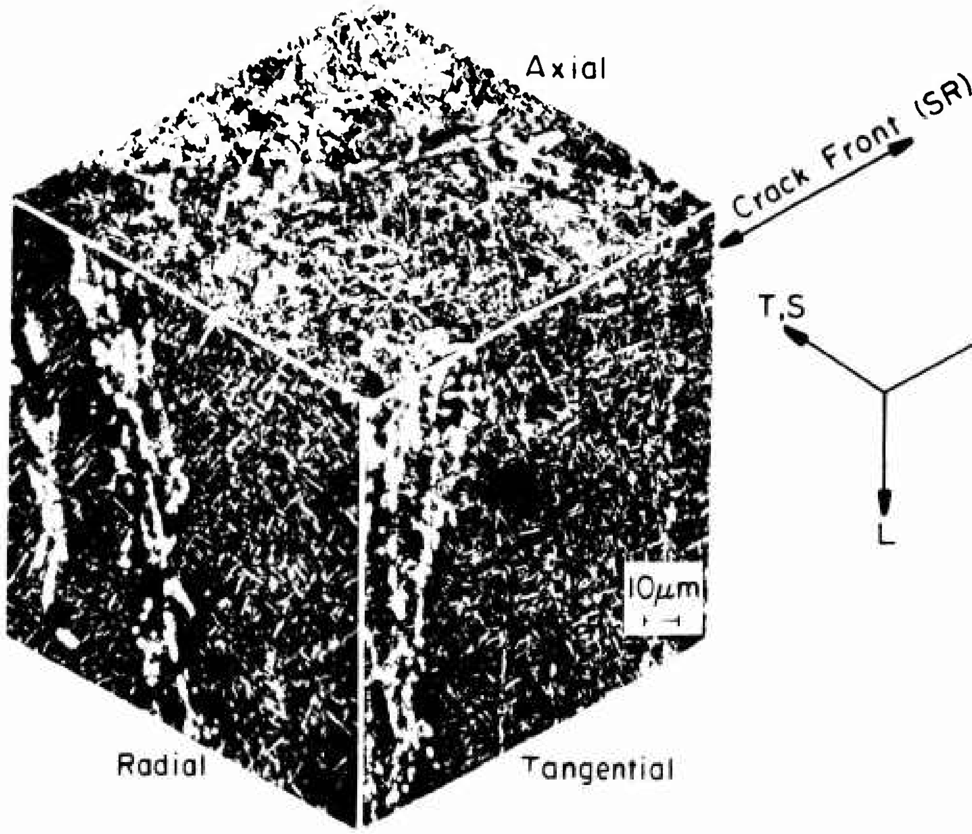


Figure 150. Alloy 334, sample 4SR12. Surface replica X5200.



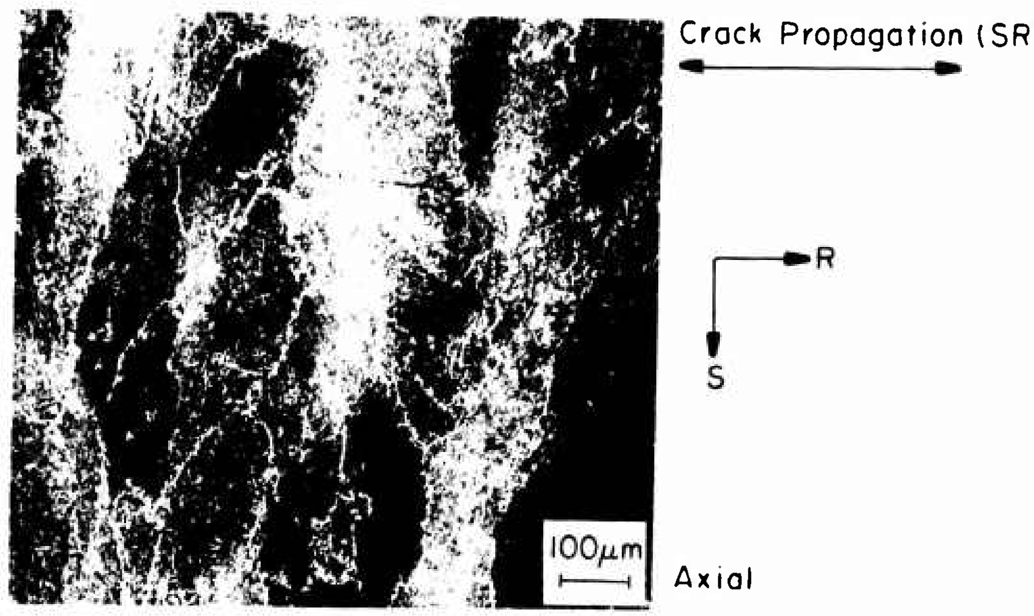


Figure 151. Alloy 227(7Mo-4Cr-2.5Al). Six inch billet slice, sample 7SR22 (Table LXI). Solution annealed 1450F - 2 hr WQ plus 1250F - 4 hr WQ, aged 950F - 8 hr. Isometric X500, axial face X100.

YS(ksi):	146 (L)	RA(%):	58 (L)	K_Q(ksi$\sqrt{in}$):	179 (LR)
	146 (T)		44 (T)		86 (SR)

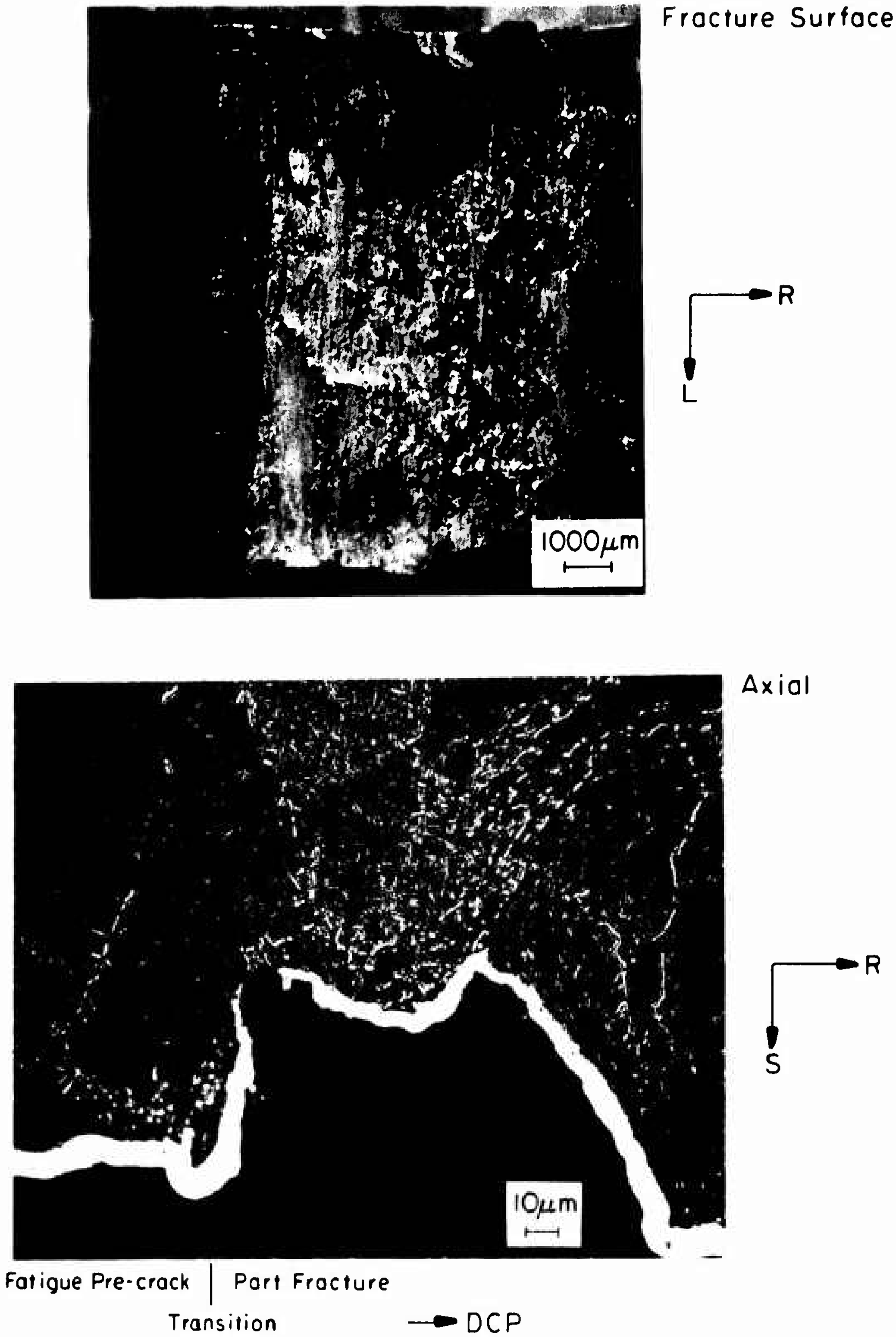


Figure 152. Alloy 227, sample 7SR22. Fracture surface X8, crack path X500.

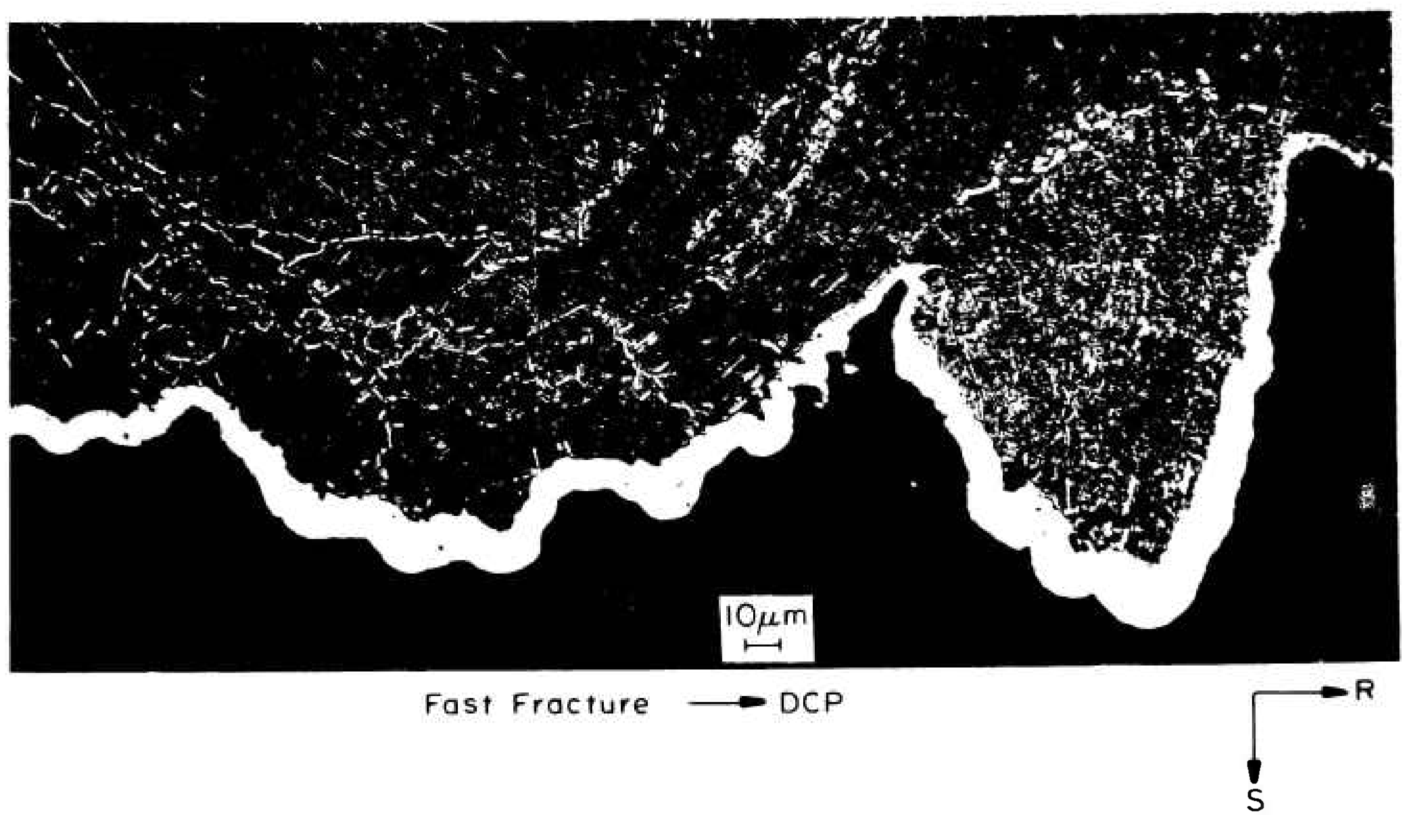


Figure 153. Alloy 227, sample 7SR22. Crack path X500.

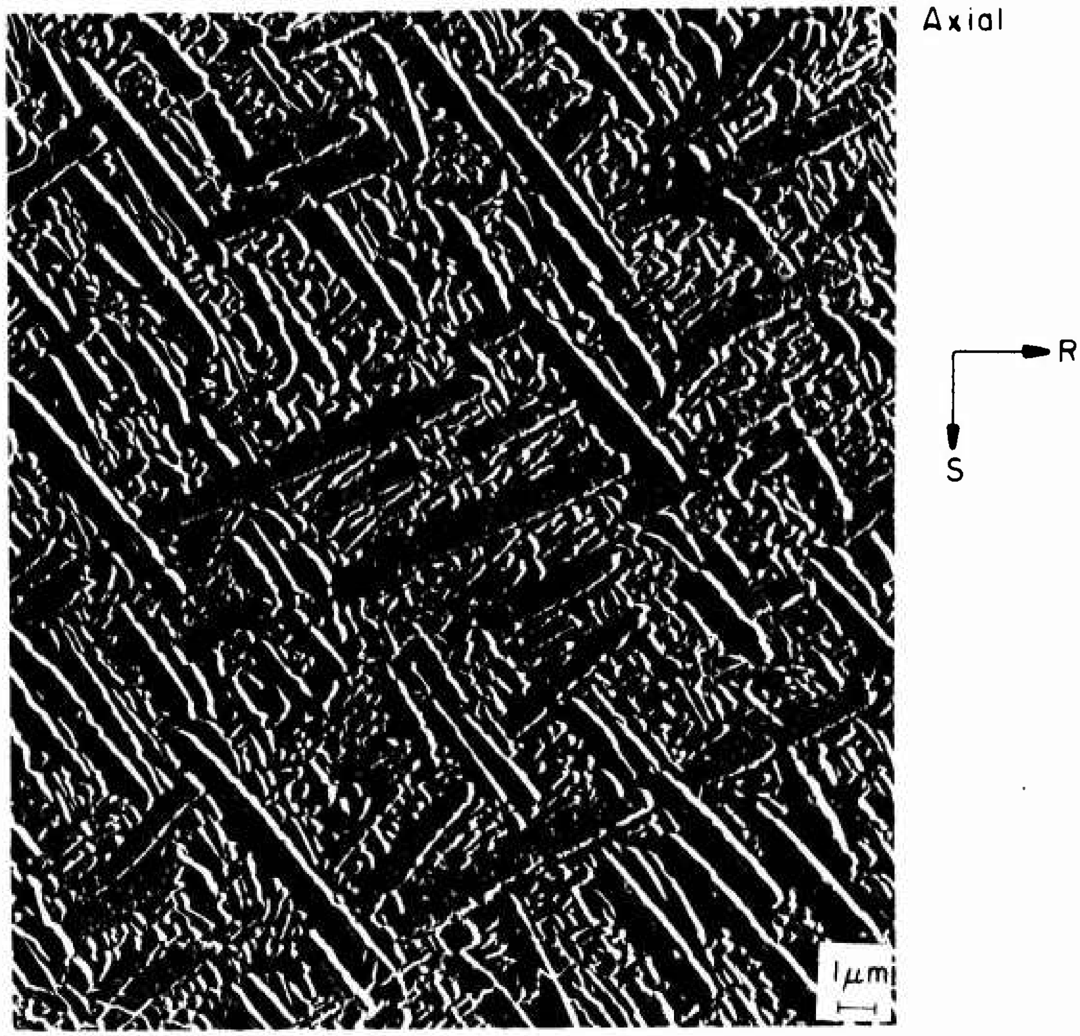
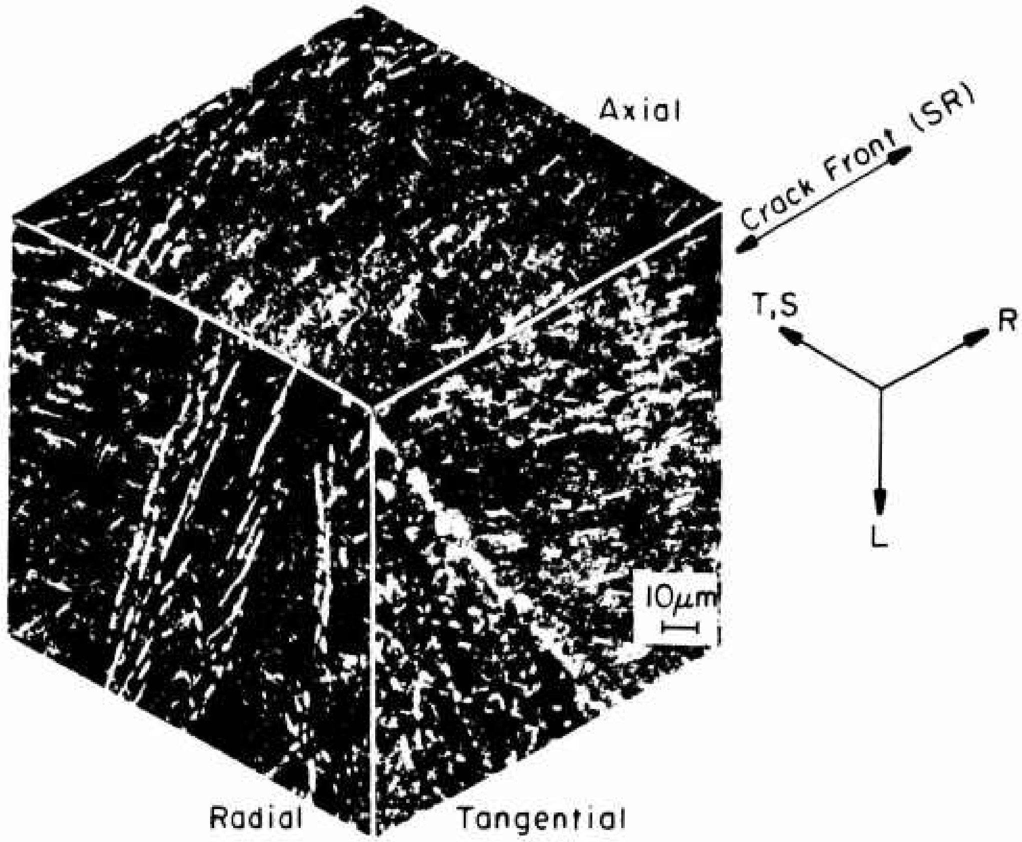


Figure 154. Alloy 227, sample 7SR22. Surface replica X5200.



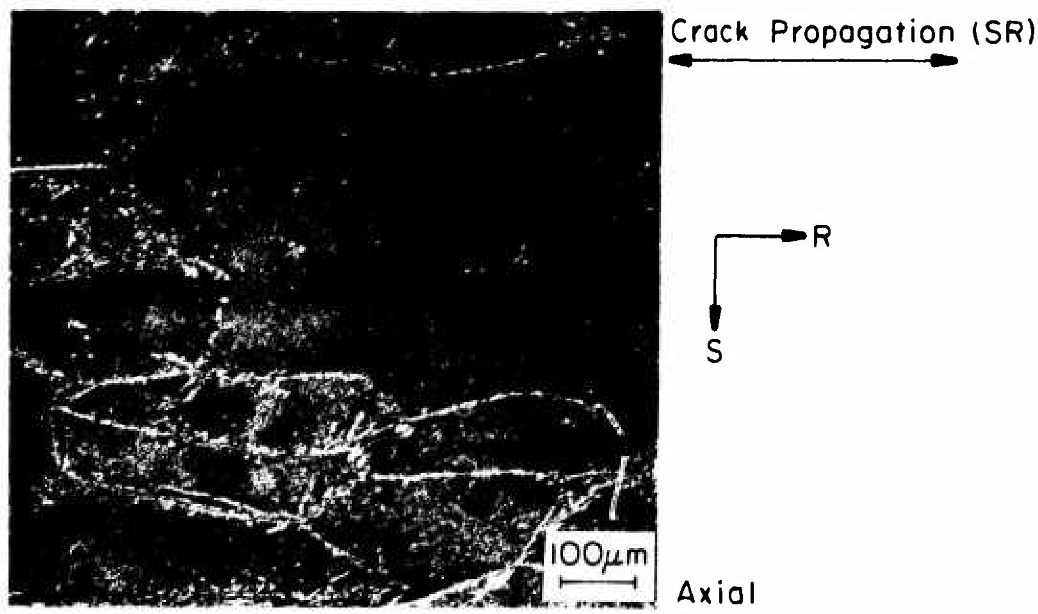


Figure 155 . Alloy 334(10Mo-6Cr-2.5Al). Six inch billet slice, sample 4SR16 (Table LVIII). Solution annealed 1250F - 8 hr WQ plus 1375F - 24 hr Wq plus 1325F - 100 hr WQ, aged 950F - 96 hr. Isometric X500, axial face X100.

YS(ksi):	167 (L)	RA(%):	31 (L)	K_Q(ksi√in):	95 (LR)
	170 (T)		6 (T)		60 (SR)

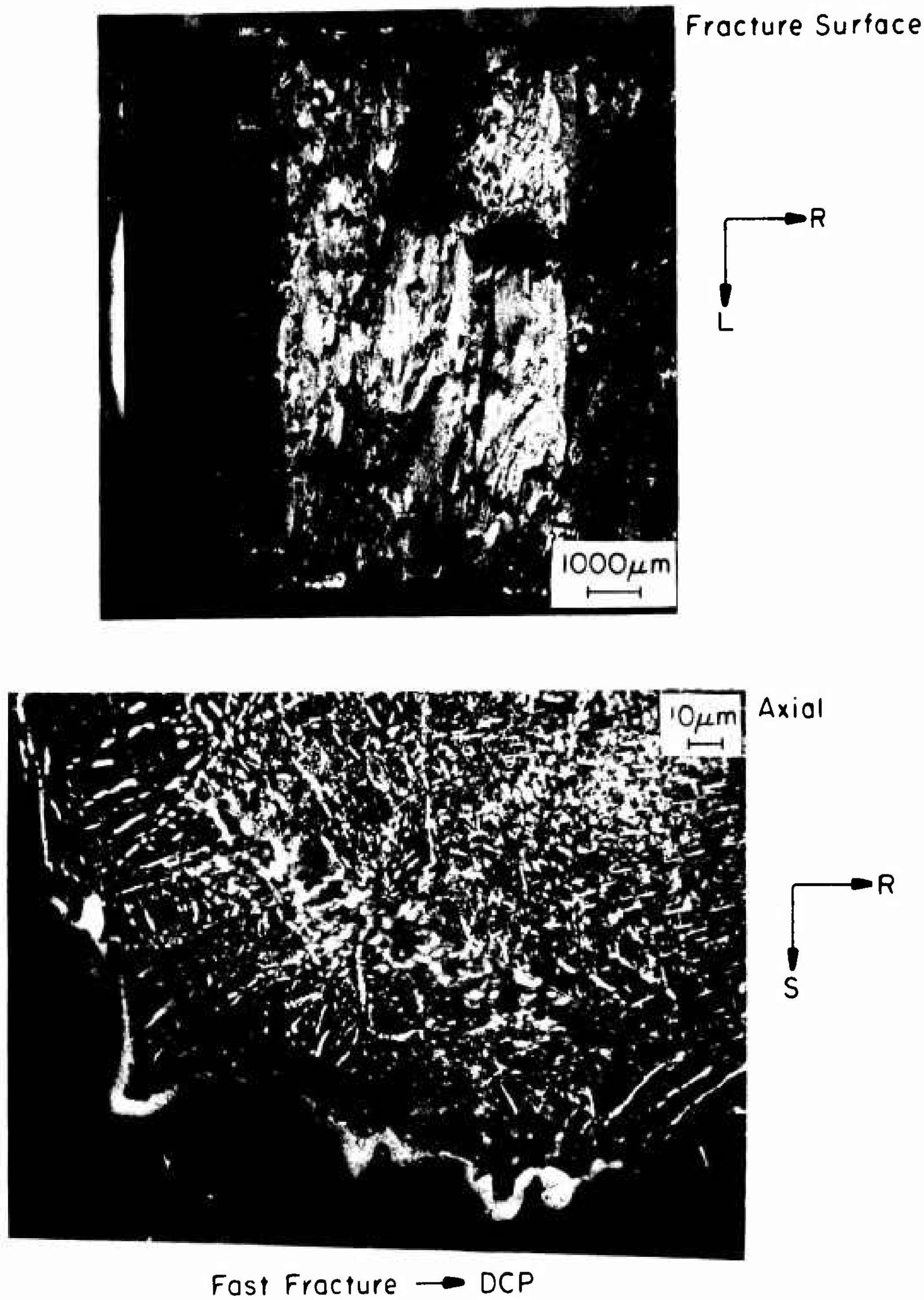


Figure 156 . Alloy 334, sample 4SR16. Fracture surface X8, crack path X500.

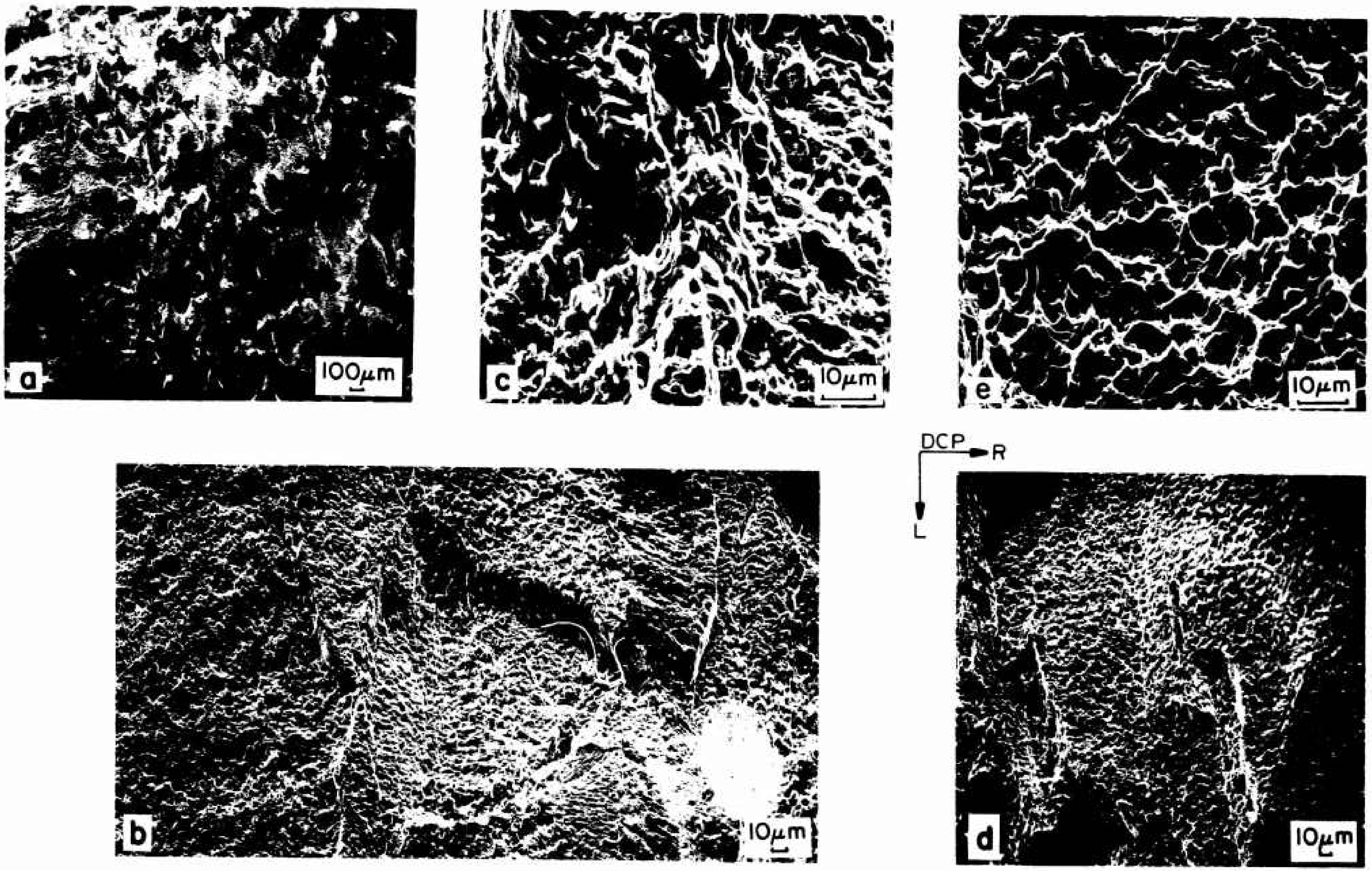


Figure 157. Alloy 334, sample 4SR16. SEM of fracture surface (a) X25, (b) X250 - precrack/fast fracture transition, (c) X250, (d) X500 - fast fracture.

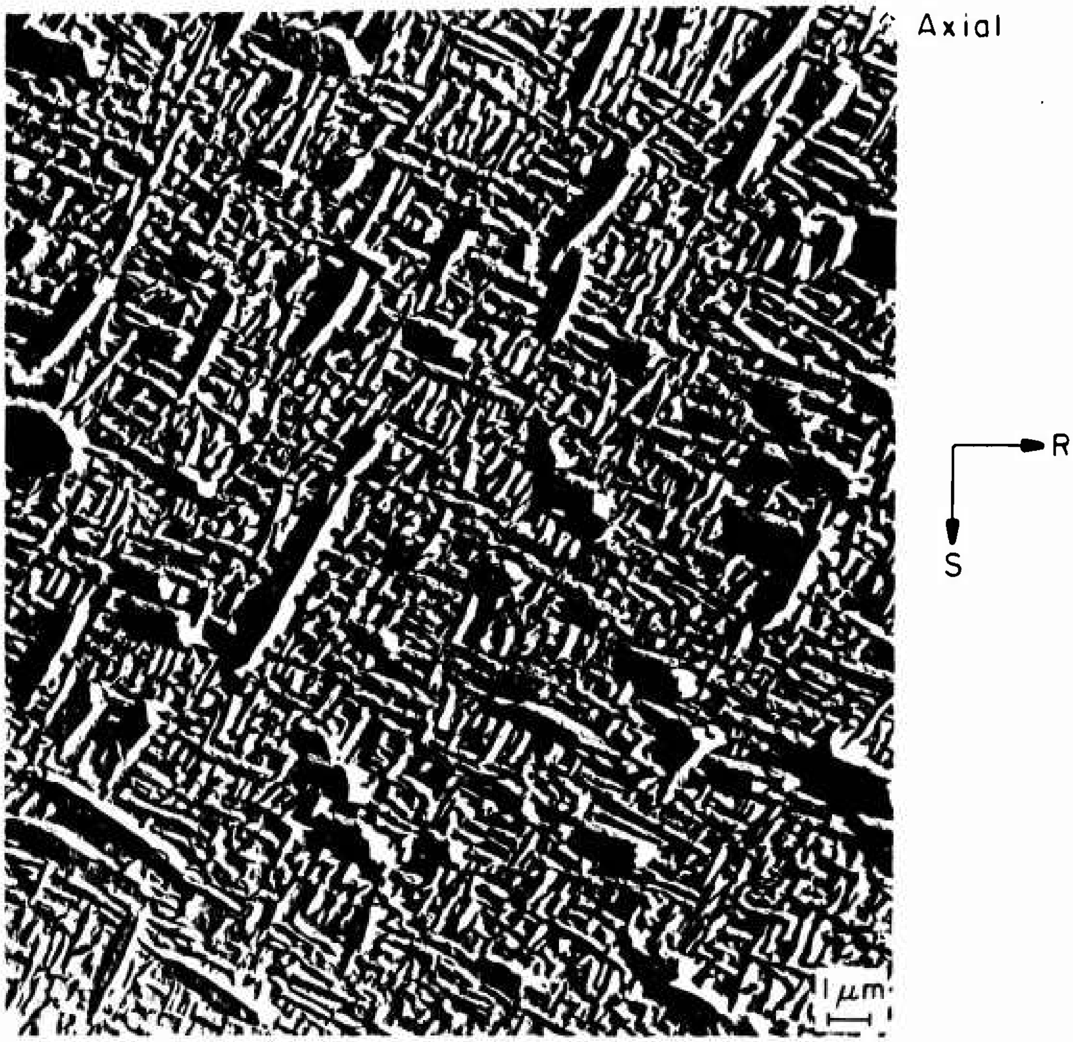


Figure 158. Alloy 334, sample 4SR16. Surface replica X5200.

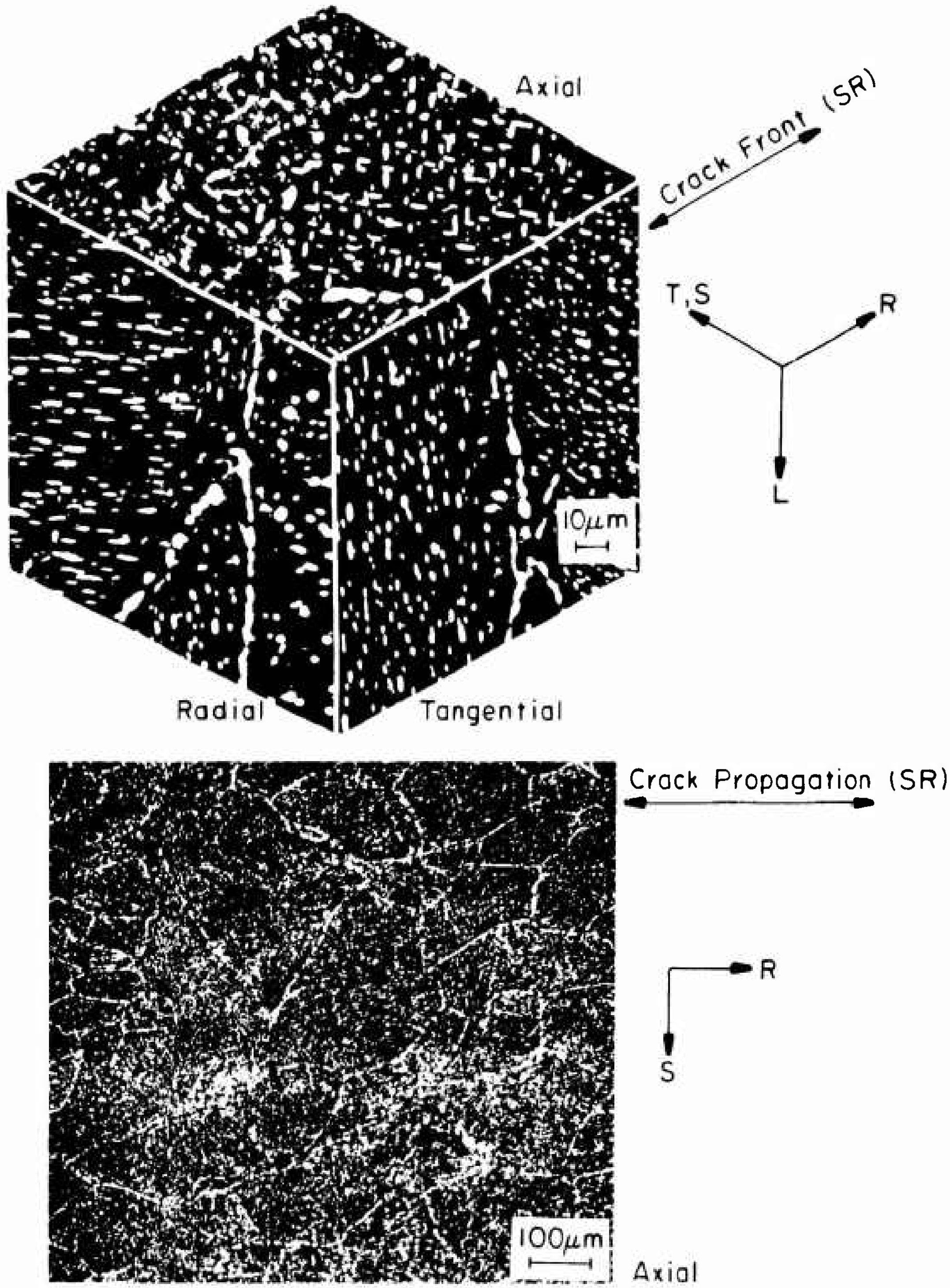


Figure 159. Alloy 227(7Mo-4Cr-2.5Al). Six inch billet slice, sample 7SR20 (Table LIX). Soluton annealed 1350F-8 hr WQ plus 1475F - 24 hr WQ plus 1425F - 100 hr WQ, aged 1025F - 8 hr. Isometric X500, axial face X100.

YS(ksi):	--- (L)	RA(%):	-- (L)	K_Q(ksi$\sqrt{in}$):	-- (LR)
	166 (T)		11 (T)		38 (SR)

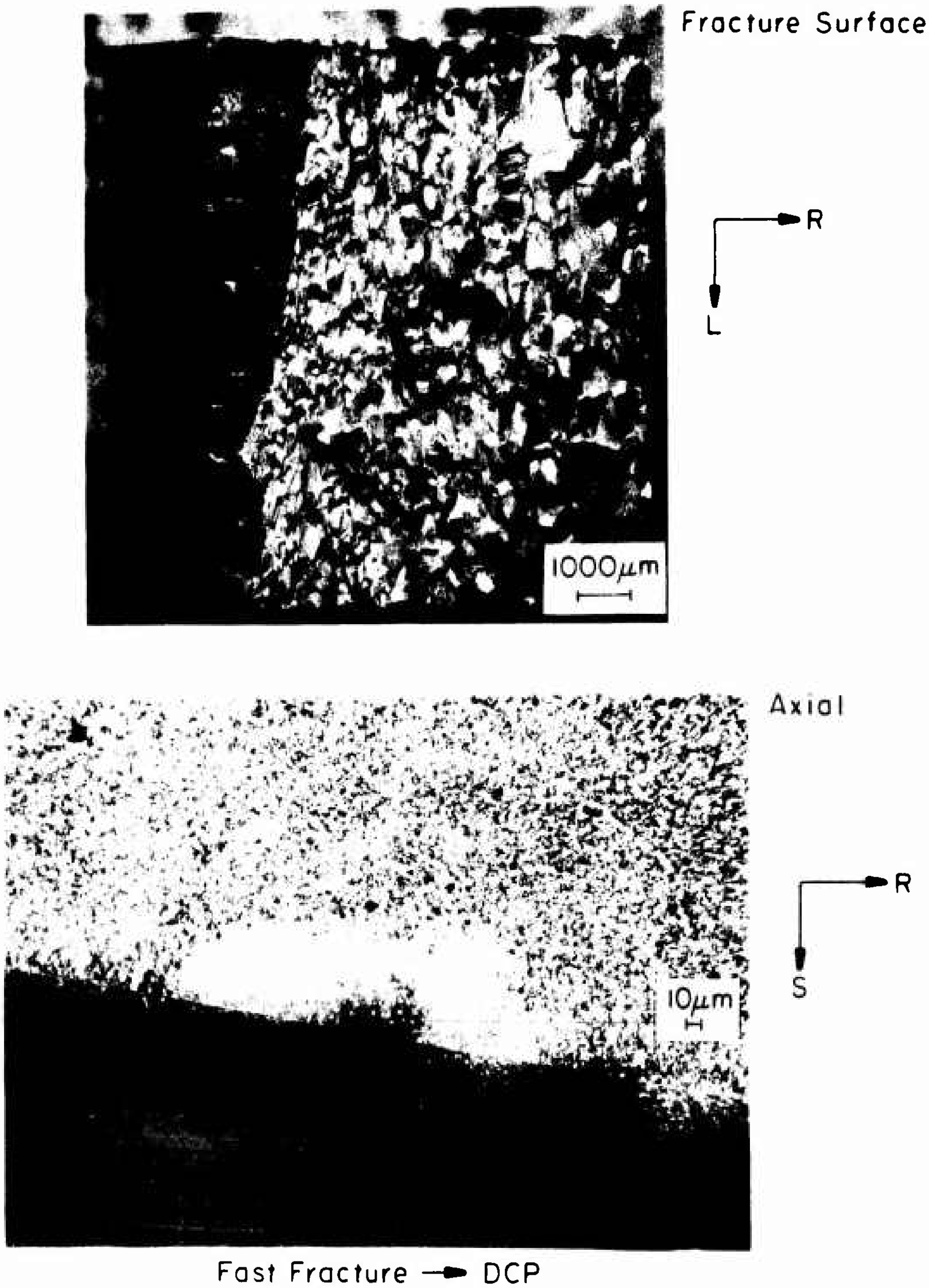


Figure 160 . Alloy 227, sample 7SR20. Fracture surface X8, crack path X250.

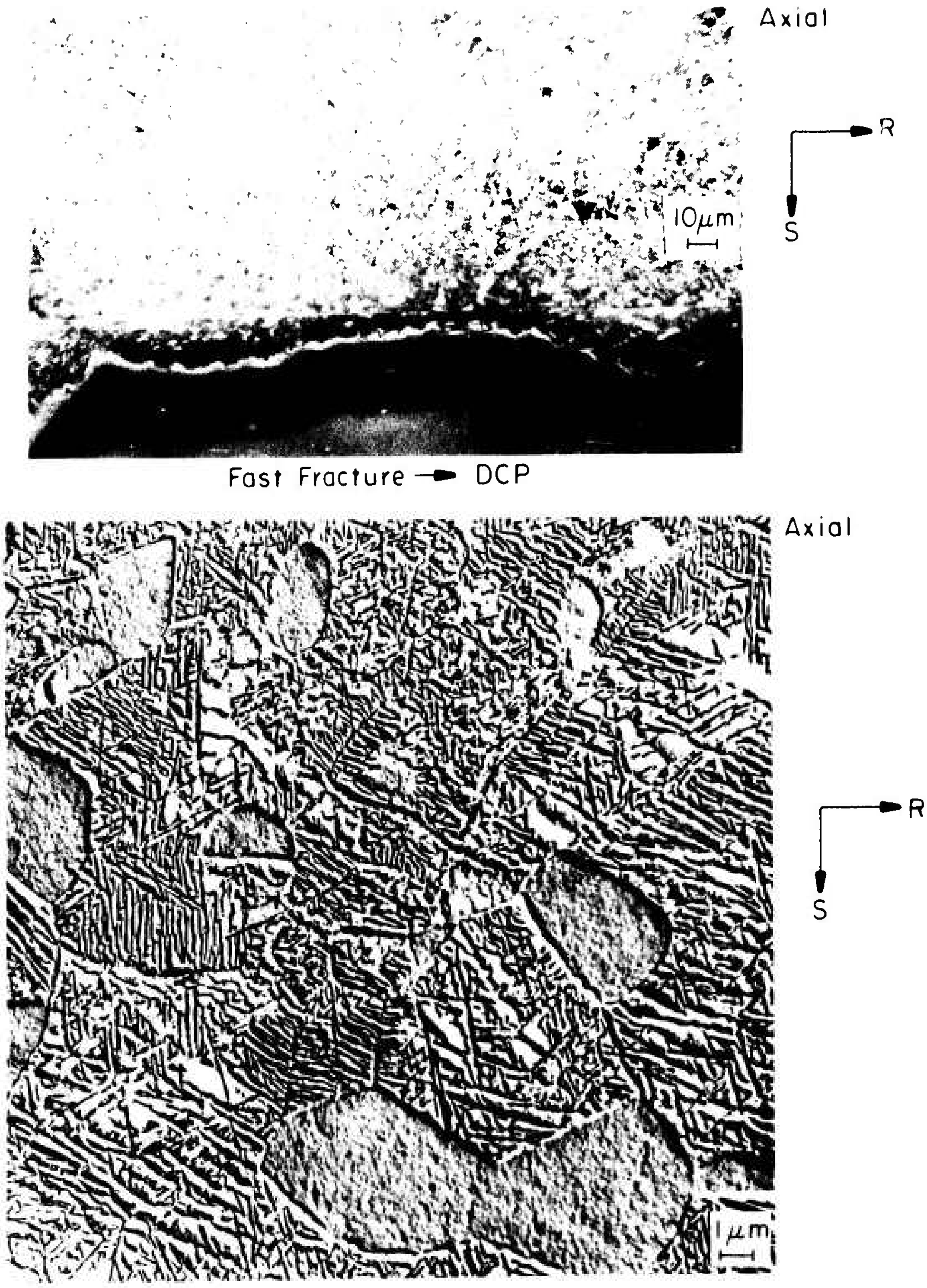


Figure 161 . Alloy 227, sample 7SR20. Crack path X500, surface replica X5200.

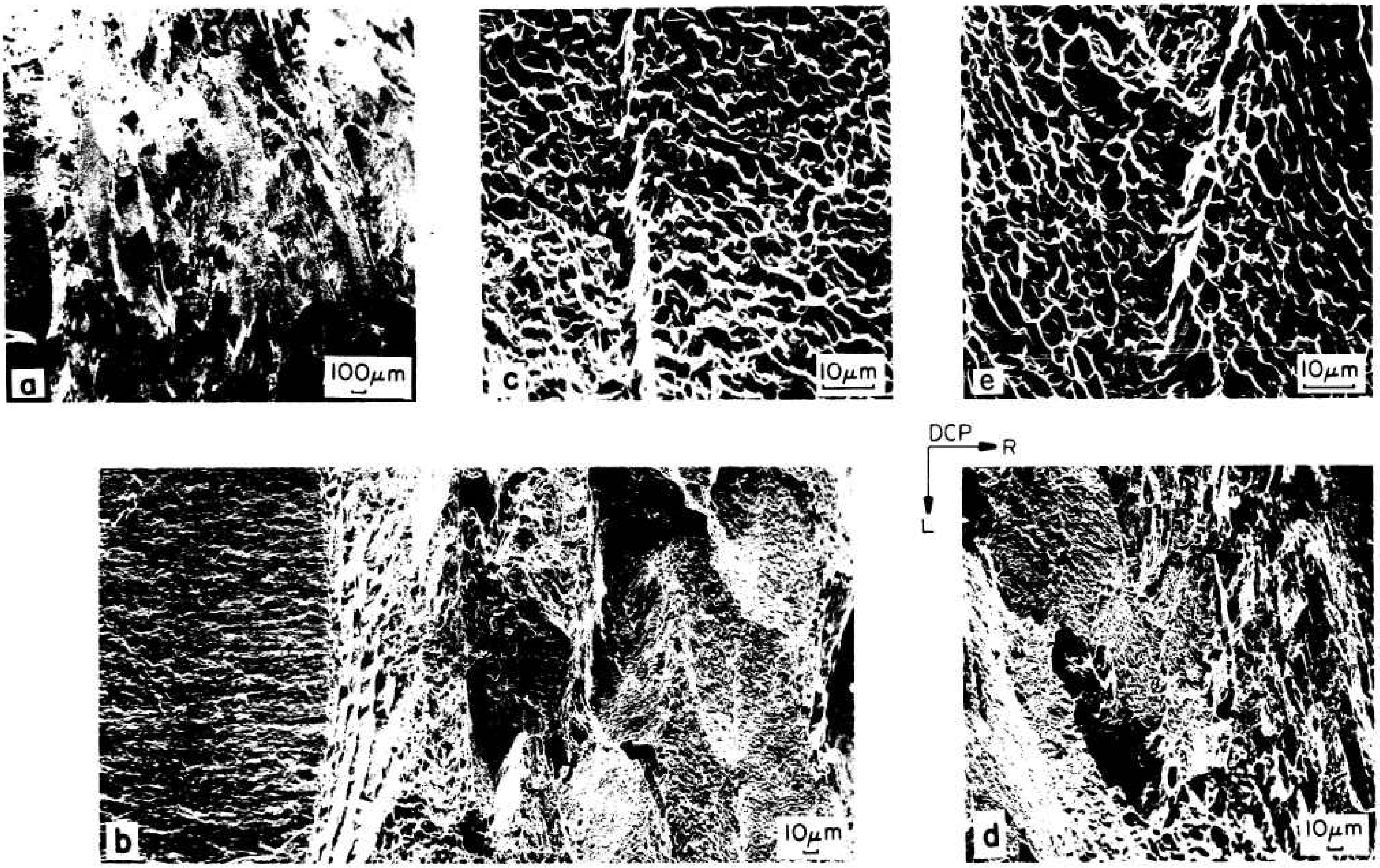


Figure 162. Alloy 227, sample 7SR20. SEM of fracture surface (a) X25, (b) X300 - precrack/fast fracture transition, (c) X1000 - close to transition, (d) X200, (e) X900 - fast fracture.

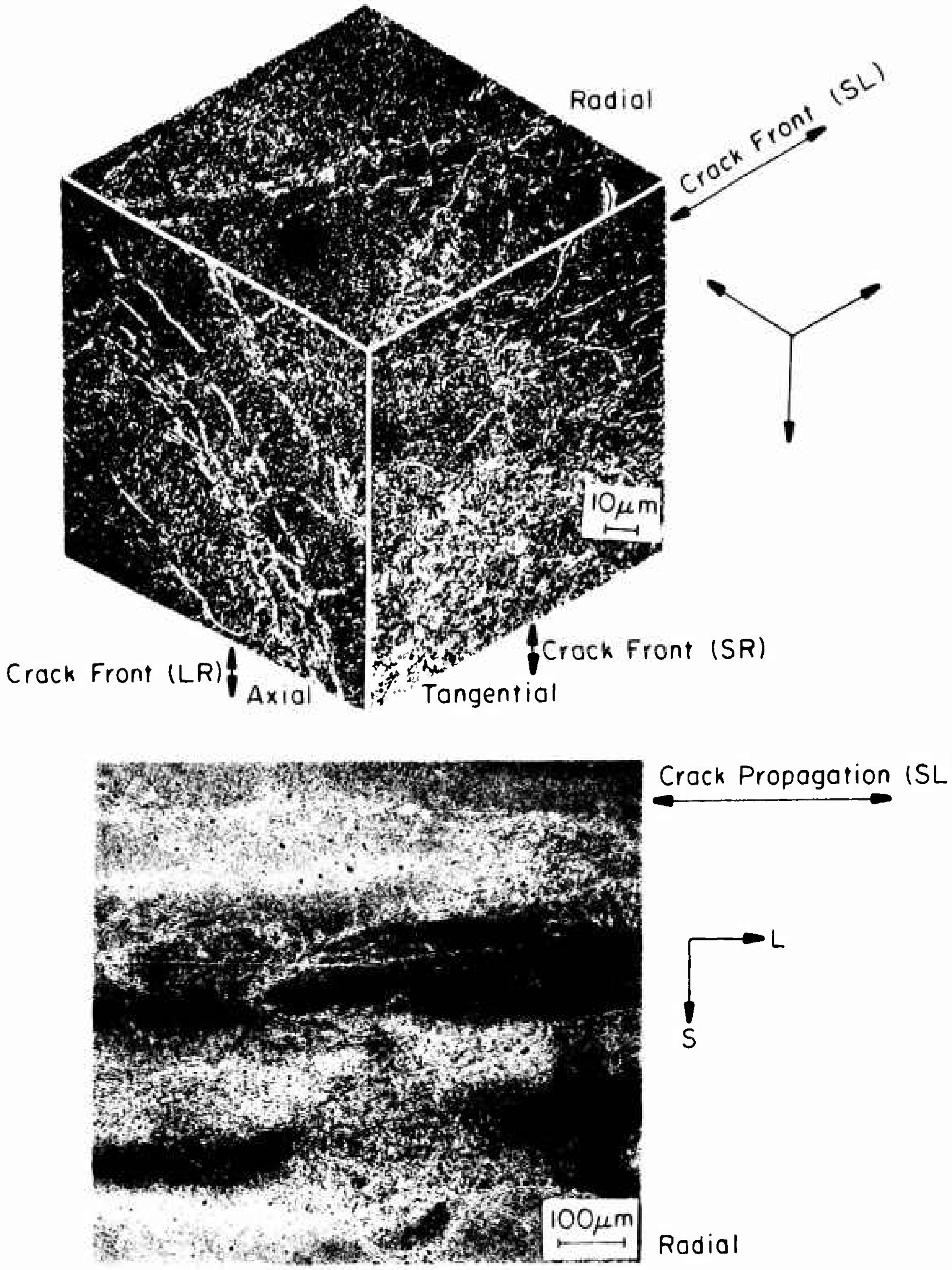


Figure 163. Alloy 334(10Mo-6Cr-2.5Al). Six inch billet full piece center samples 4SLC2 and 4LRC2 (Table LXVI). Solution annealed 1350F-4 hr Wq plus 1225F-2 hr WQ, aged 900F-96 hr. Isometric X500, radial face X100.

YS(ksi):	147 (L)	RA(%):	50 (L)	K_Q(ksi$\sqrt{in}$):	126 (LR)
	151 (T)		33 (T)		70 (SL)

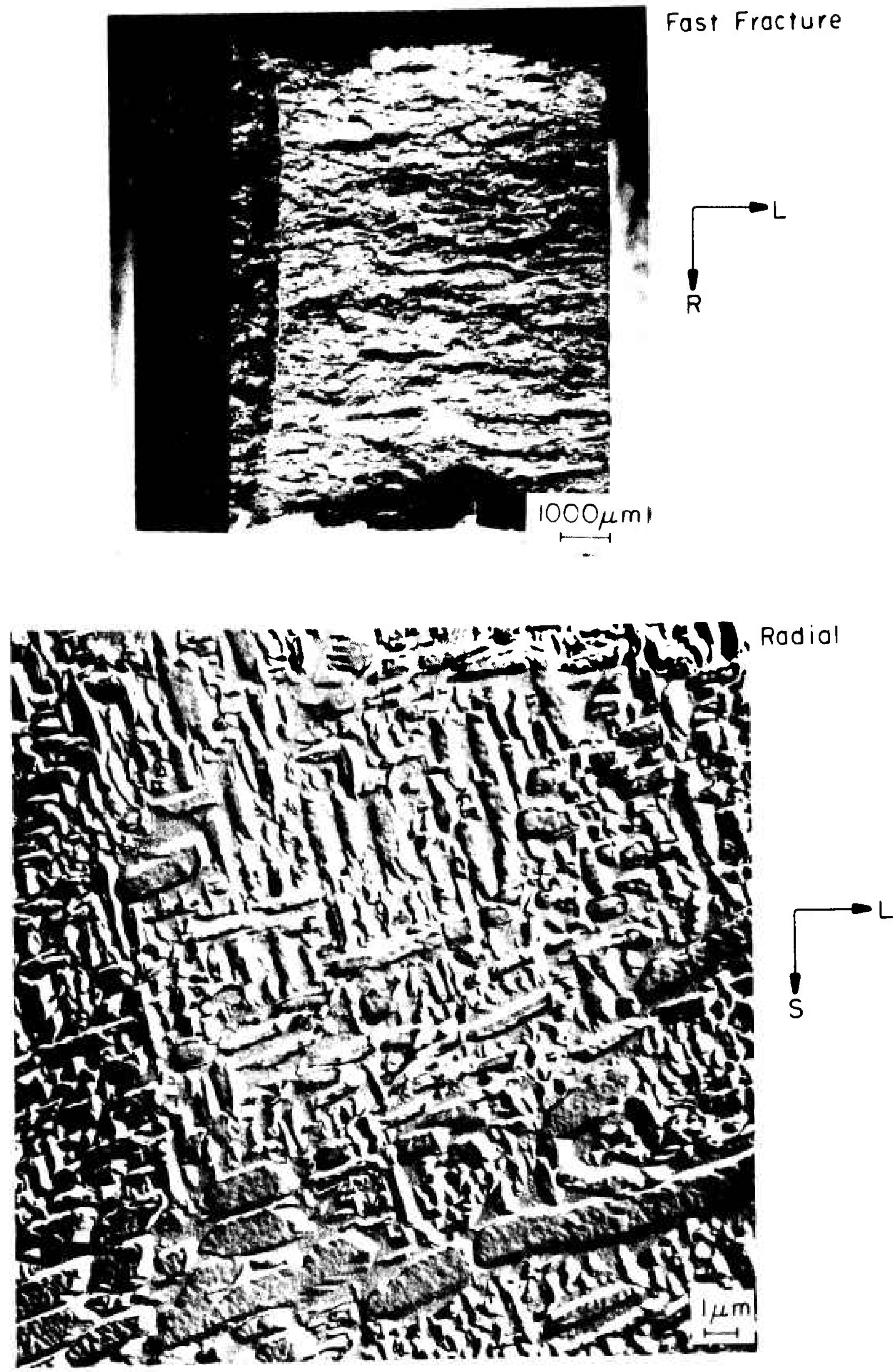


Figure 164. Alloy 334, sample 4SLC2. Fracture surface X8, surface replica X5200.

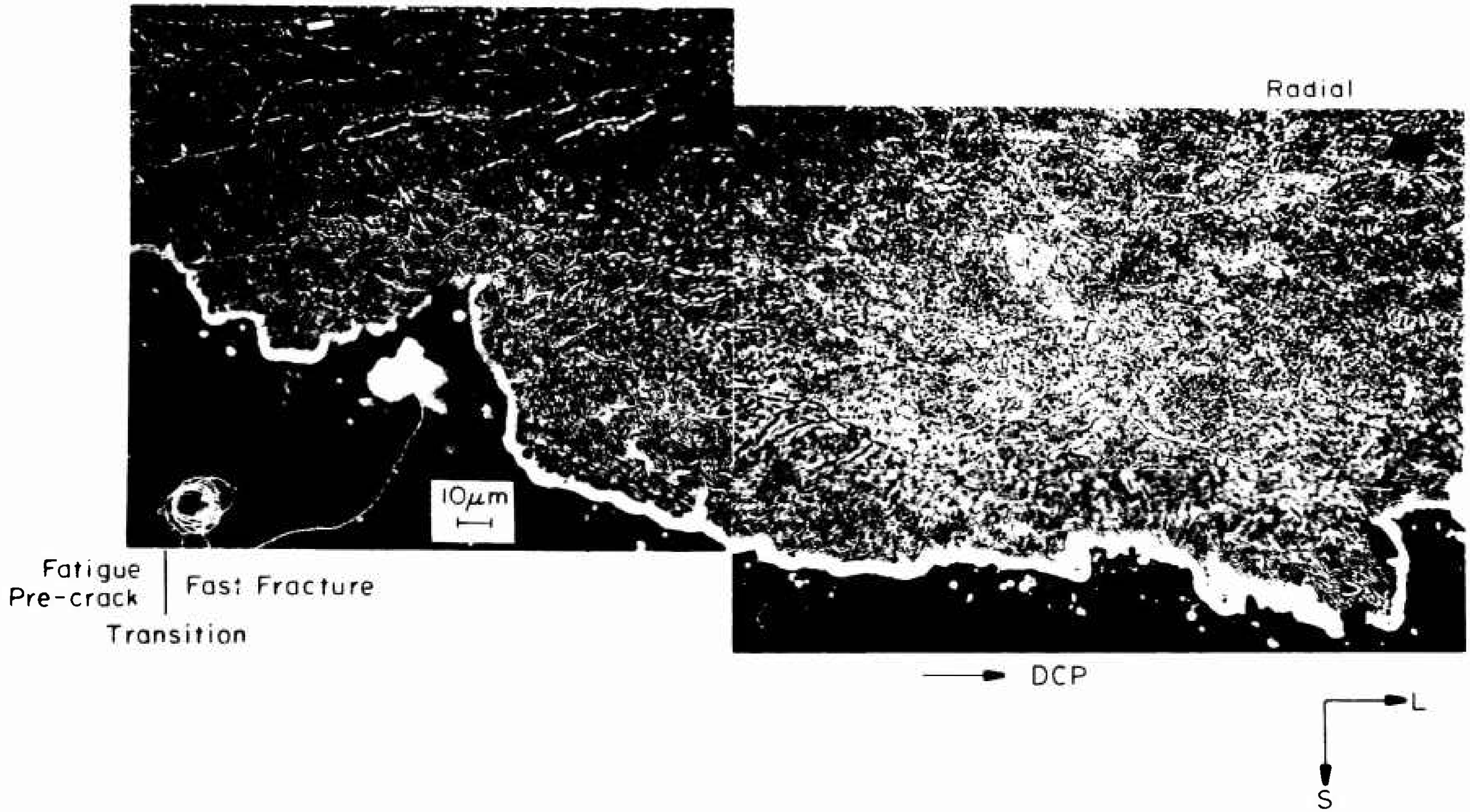


Figure 165. Alloy 334, sample 4SLC2. Crack path X500.

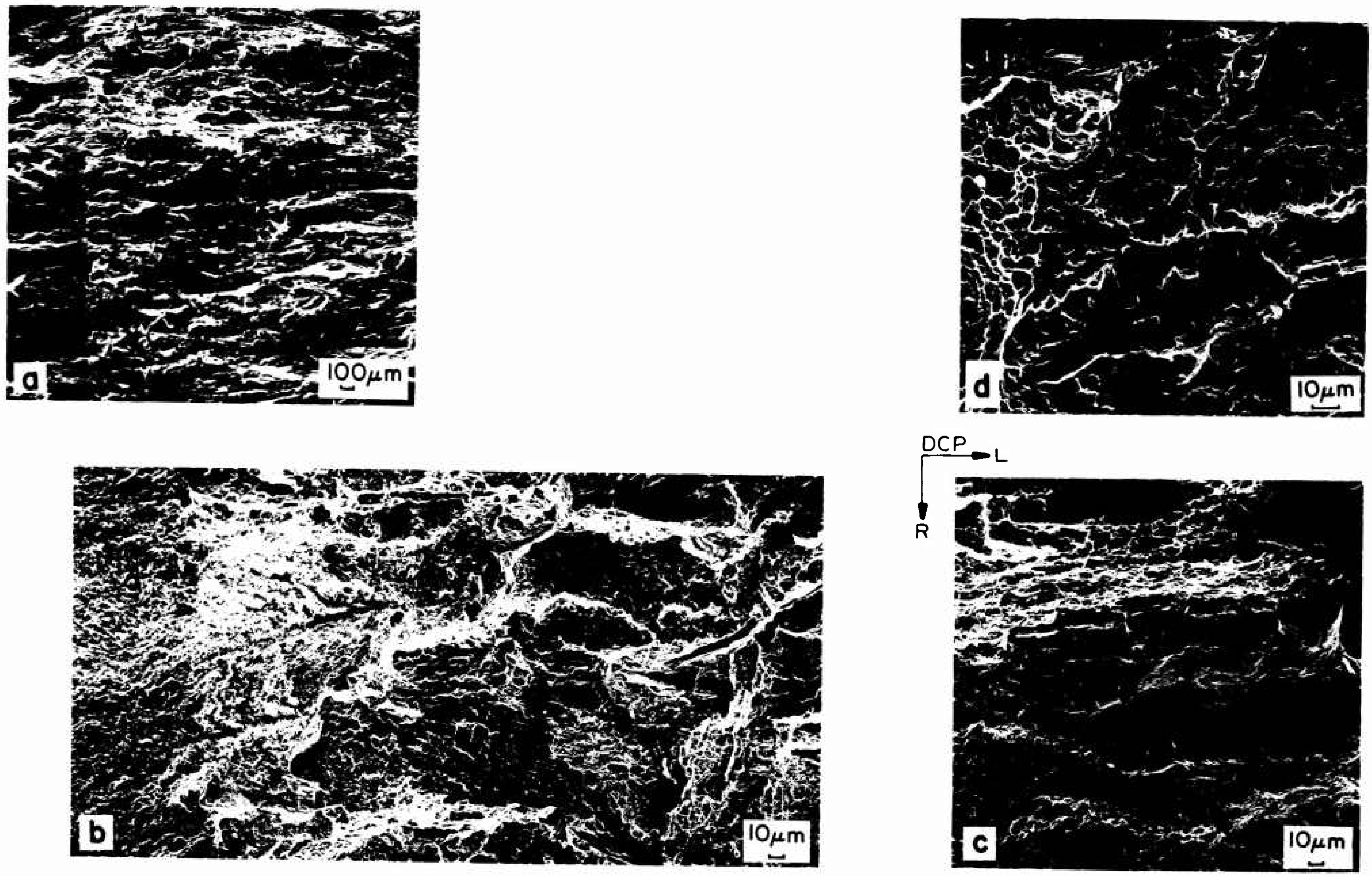
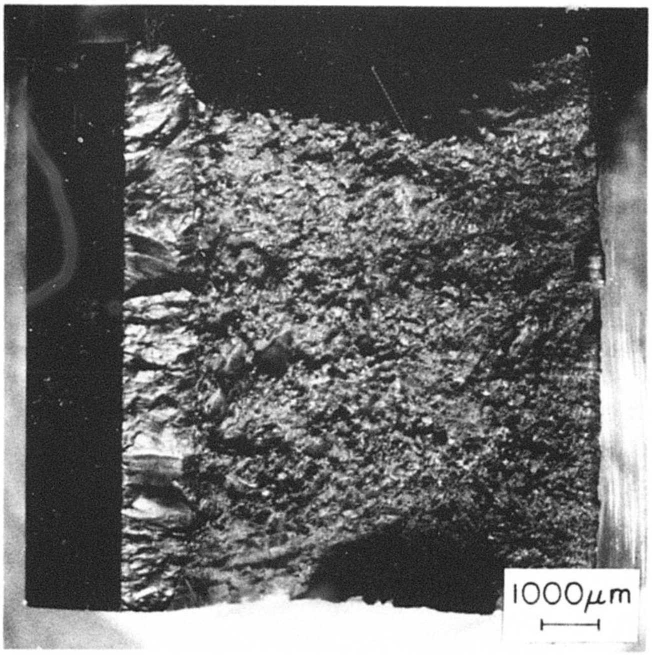


Figure 166. Alloy 334, sample 4SLC2. SEM of fracture surface (a) X25, (b) X250-precrack/fast fracture transition, (c) X250, (d) X500 - fast fracture.



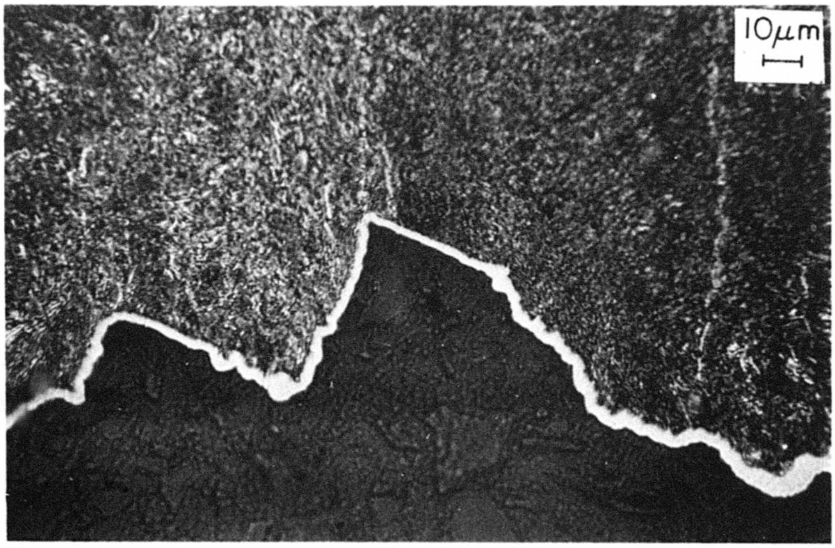


Figure 167. Alloy 334, sample 4LRC2. Fracture surface X8, crack path X500.

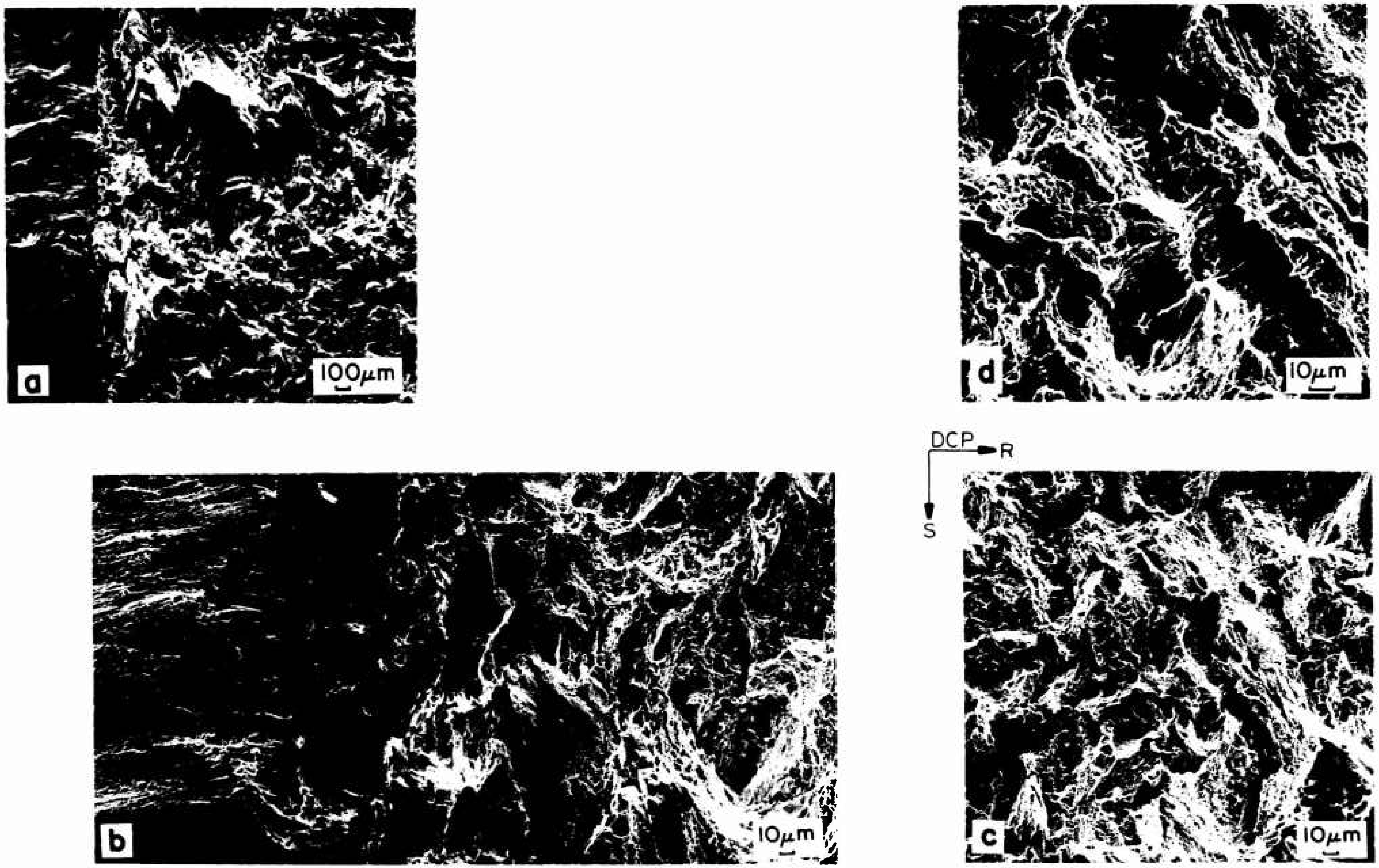


Figure 168. Alloy 334, sample 4LRC2. SEM of fracture surface (a) X25, (b) X250 - precrack/ fast fracture transition, (c) X250, (d) X500 - fast fracture.

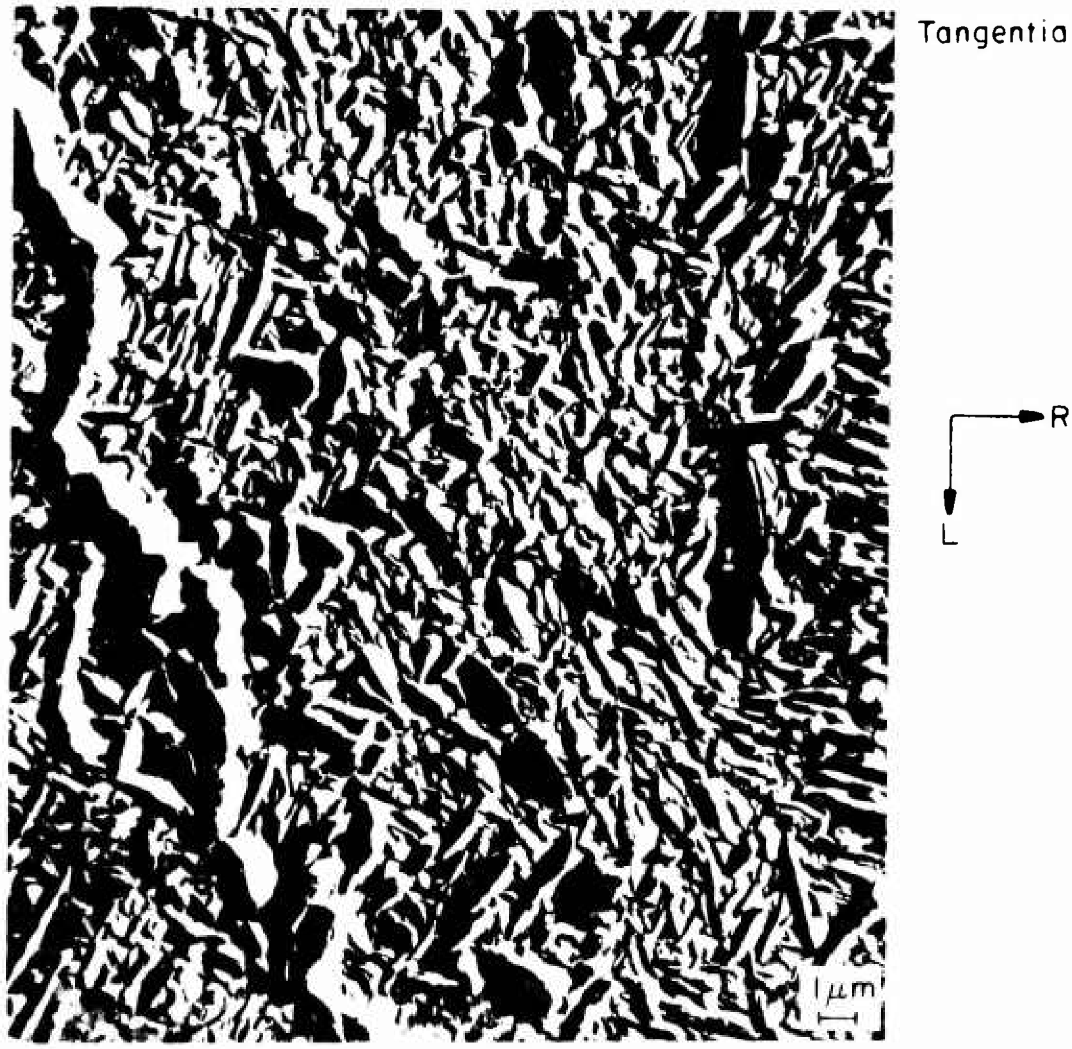
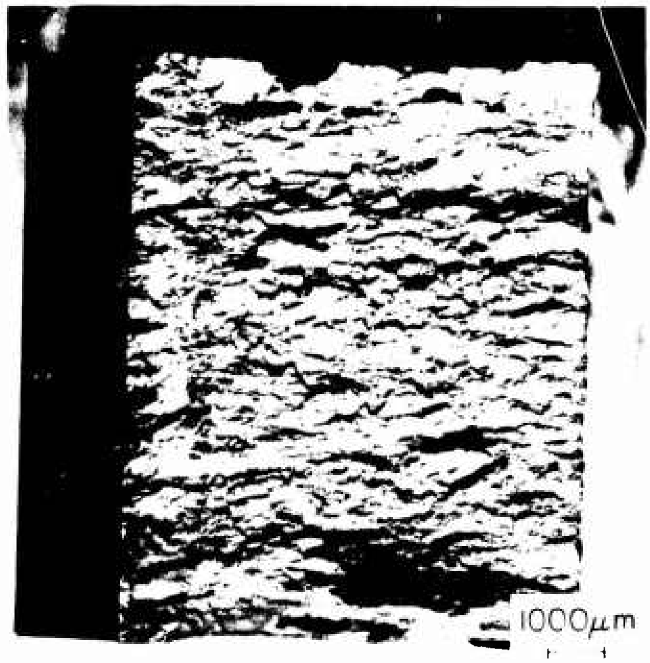


Figure 169. Alloy 334, sample 4LRC2. Surface replica X5200.



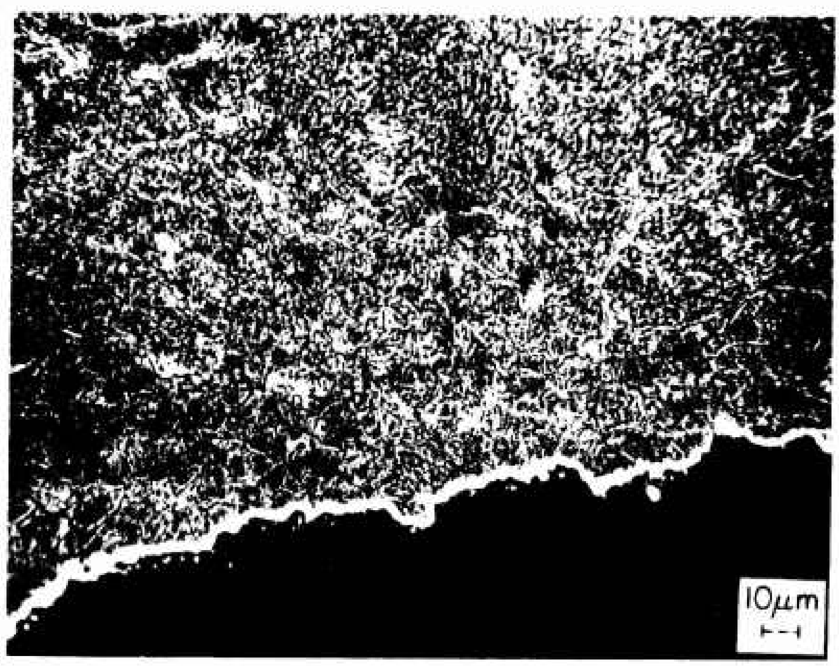


Figure 170. Alloy 334(10Mo-6Cr-2.5Al). Six inch billet full piece, center sample 4SLC4. (Table LXXII). Solution annealed 1350F-4 hr WQ plus 1225F-2 hr WQ, aged 1000F-96 hr. Fracture surface X8, crack path X500.

YS(ksi):	144 (L)	RA(%):	37 (L)	K_Q(ksi√in):	-- (LR)
	146 (T)		34 (T)		75 (SL)

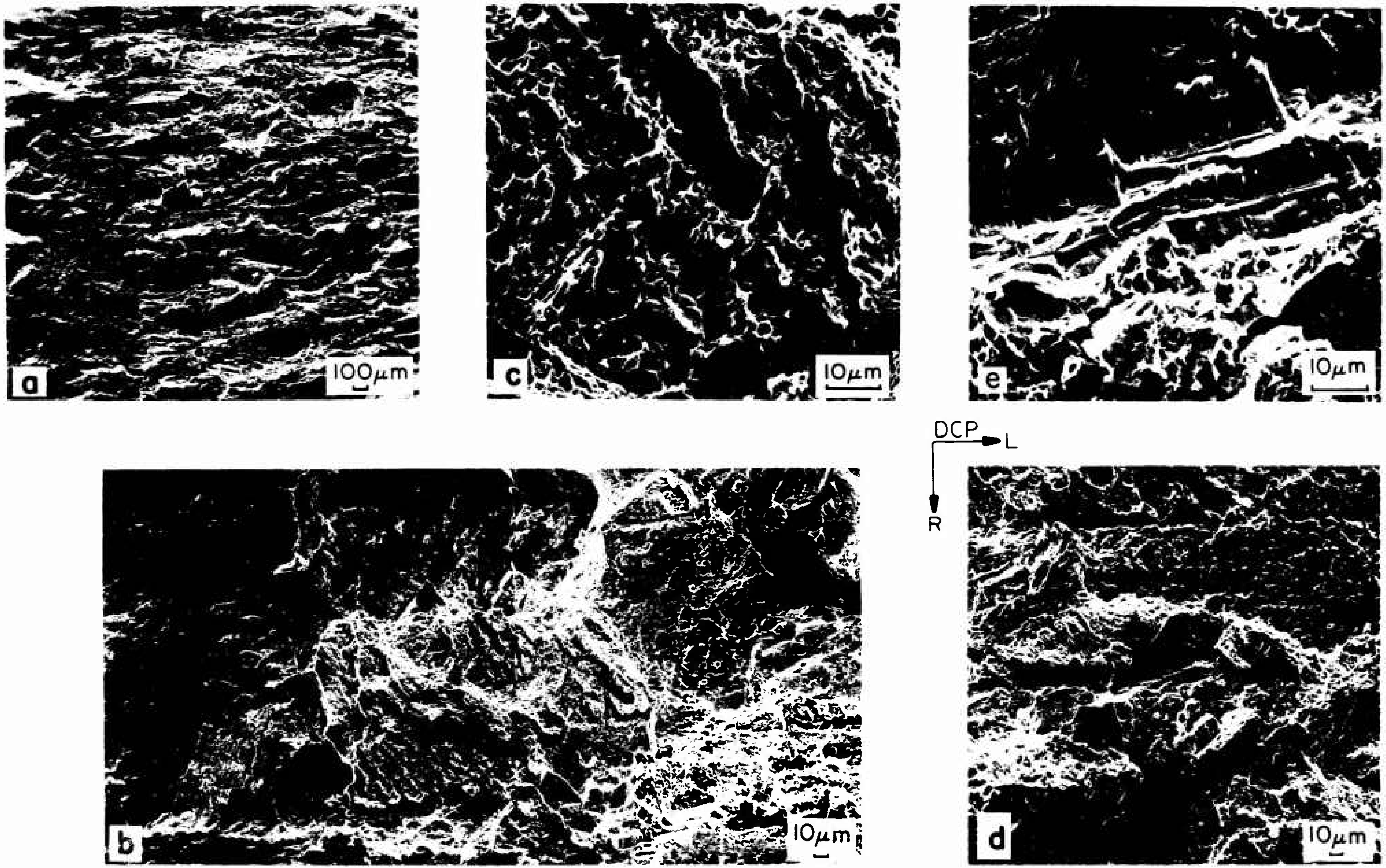


Figure 171 . Alloy 334, sample 4SLC4. SEM of fracture surface (a) X25, (b) X250 - precrack/ fast fracture transition, (c) X1000 - fast fracture close to transition, (d) X200, (e) X1000- fast fracture.

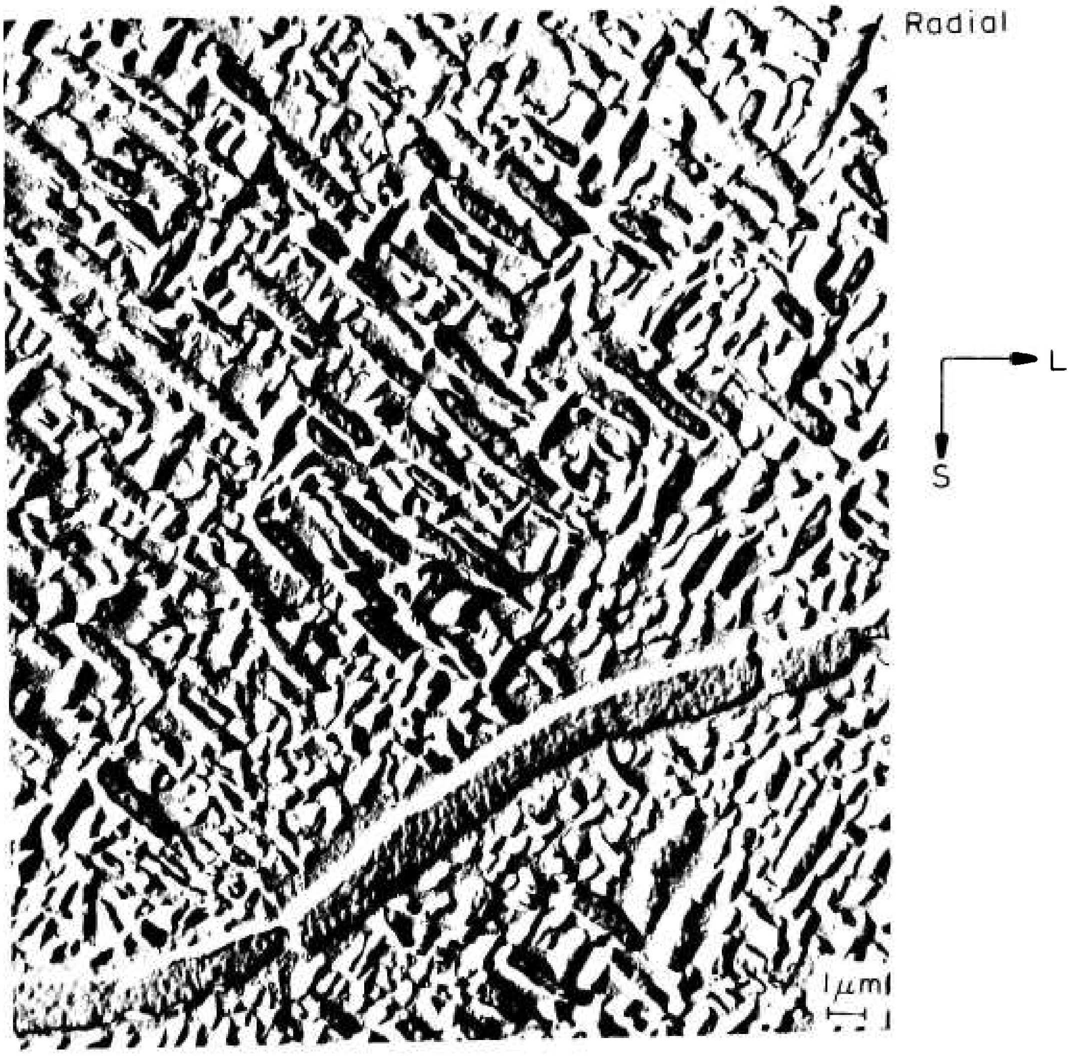


Figure 172. Alloy 334, sample 4SLC4. Surface replica X5200.

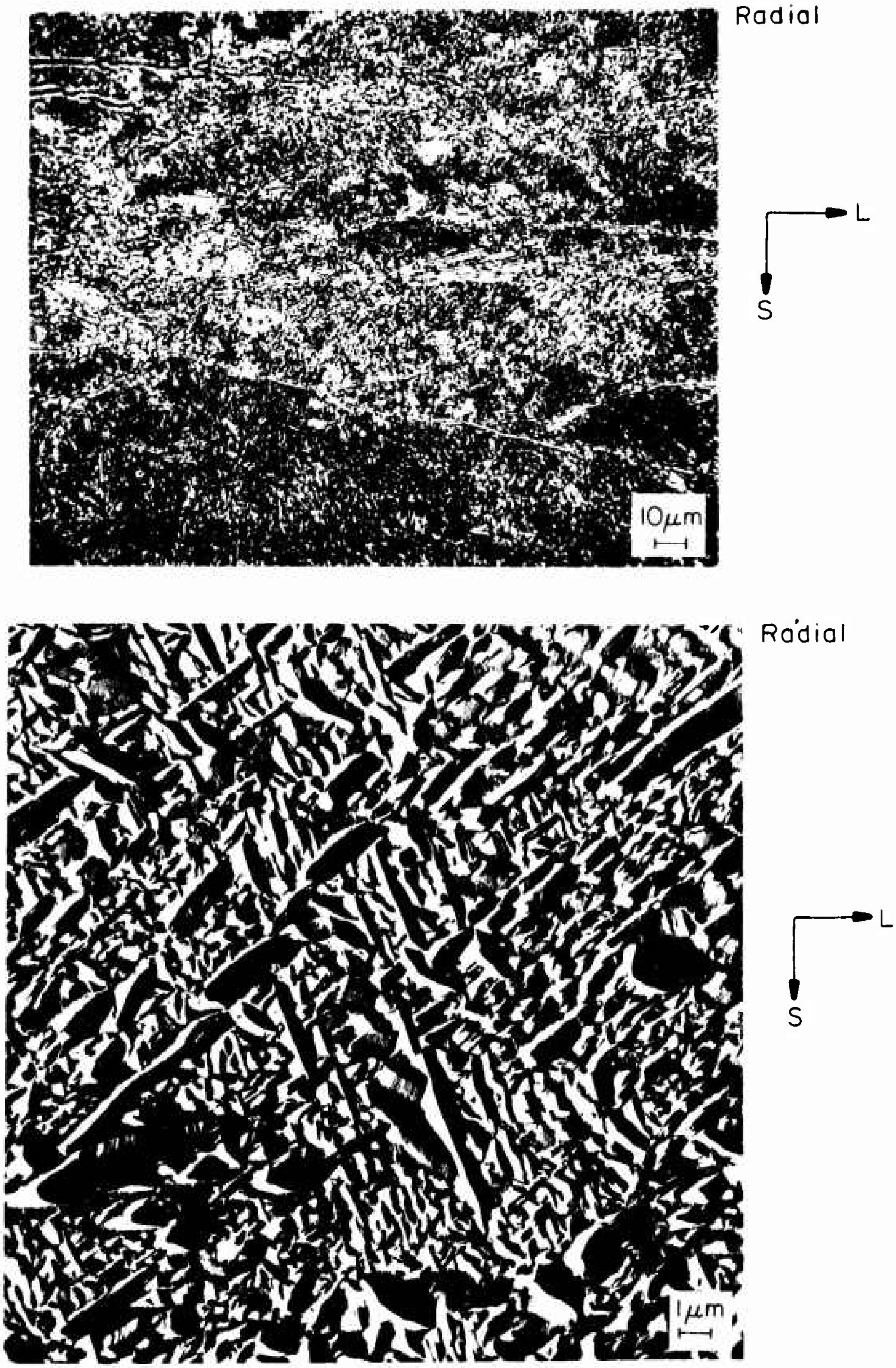


Figure 173. Alloy 334(10Mo-6Cr-2.5Al). Six inch billet full piece, edge samples 4SLE2 and 4LRE2 (Table LXVI). Solution annealed 1350F-4 hr WQ plus 1225F-2 hr WQ, aged 900F-96 hr. Radial face X500, surface replica X5200.

YS(ksi):	155 (L)	RA(%):	53 (L)	K_Q(ksi$\sqrt{in}$):	134 (LR)
	150 (T)		23 (T)		59 (SL)

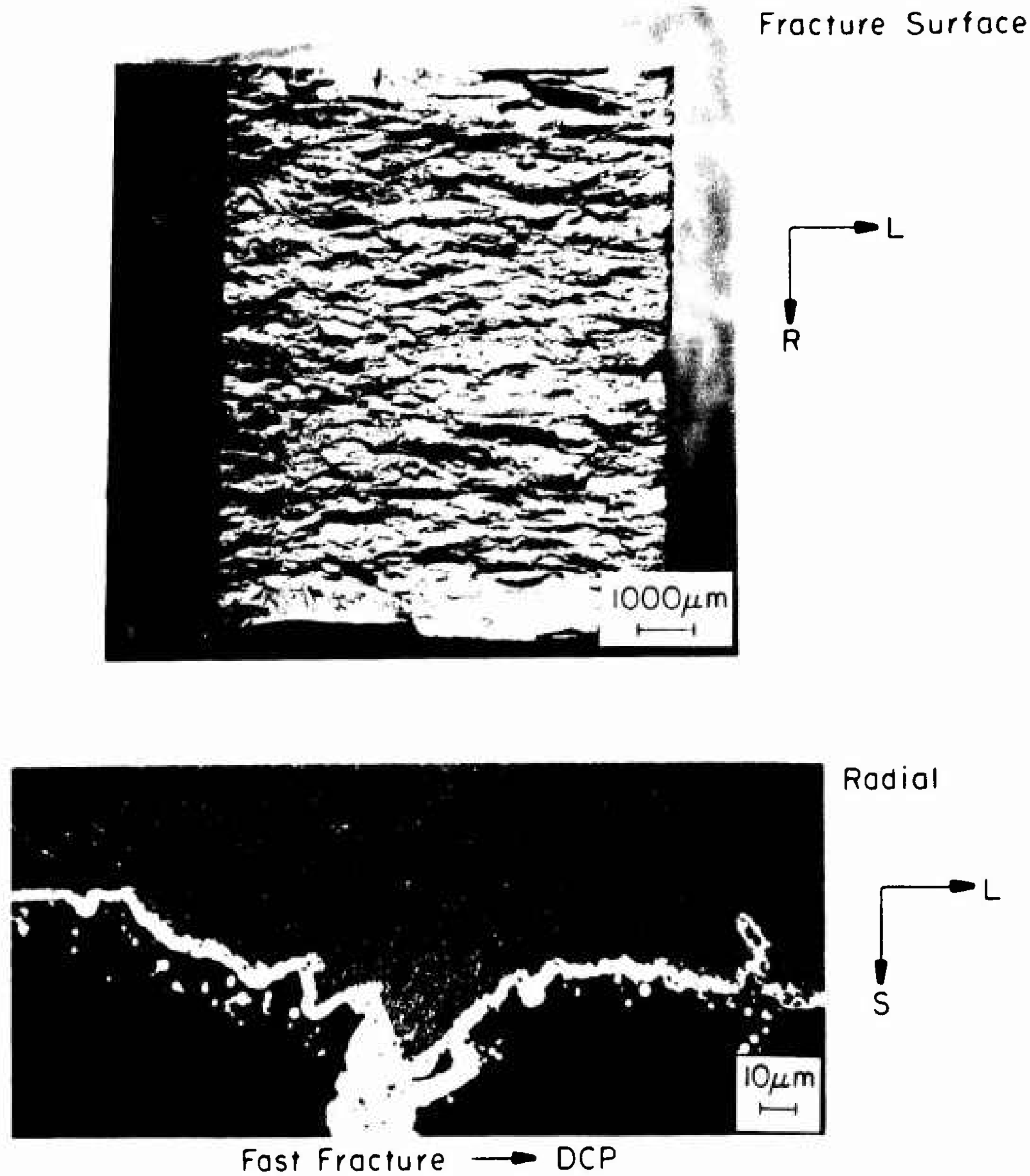


Figure 174. Alloy 334, sample 4SLE2. Fracture surface X8, crack path X500.

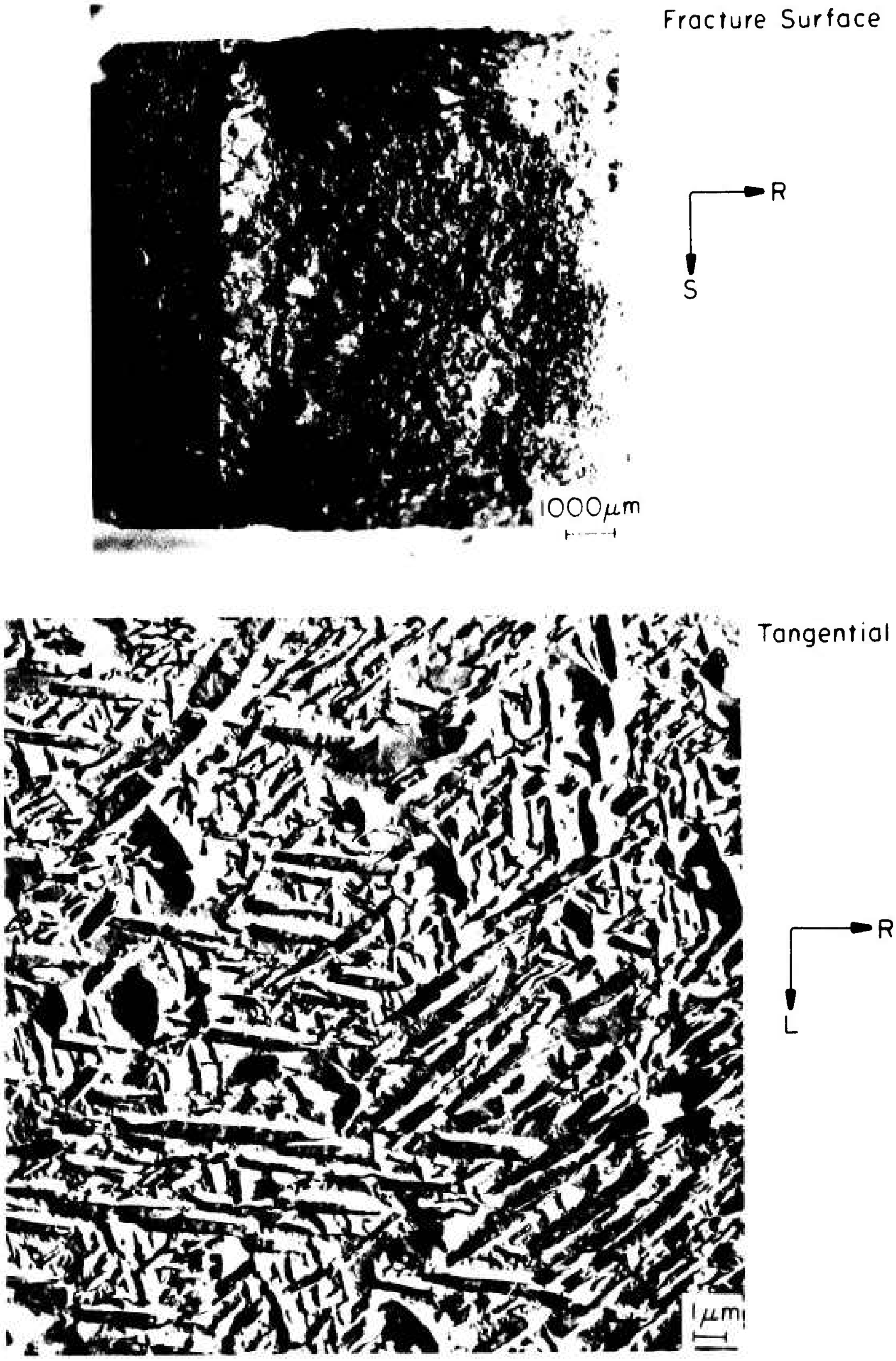


Figure 175. Alloy 334, sample 4LRE2. Fracture surface X8, surface replica X5200.

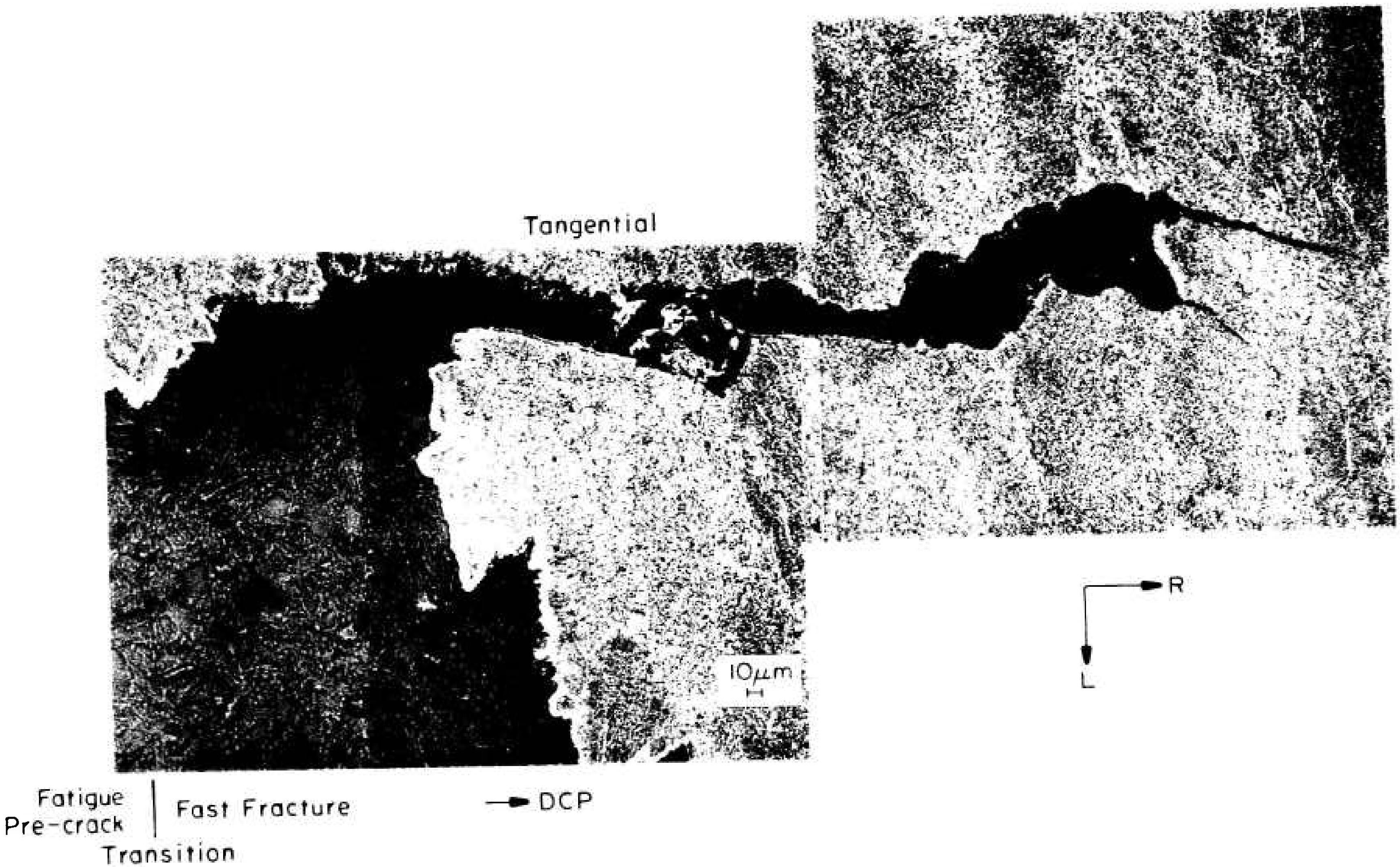


Figure 176. Alloy 334, sample 4LRE2. Crack path X250.

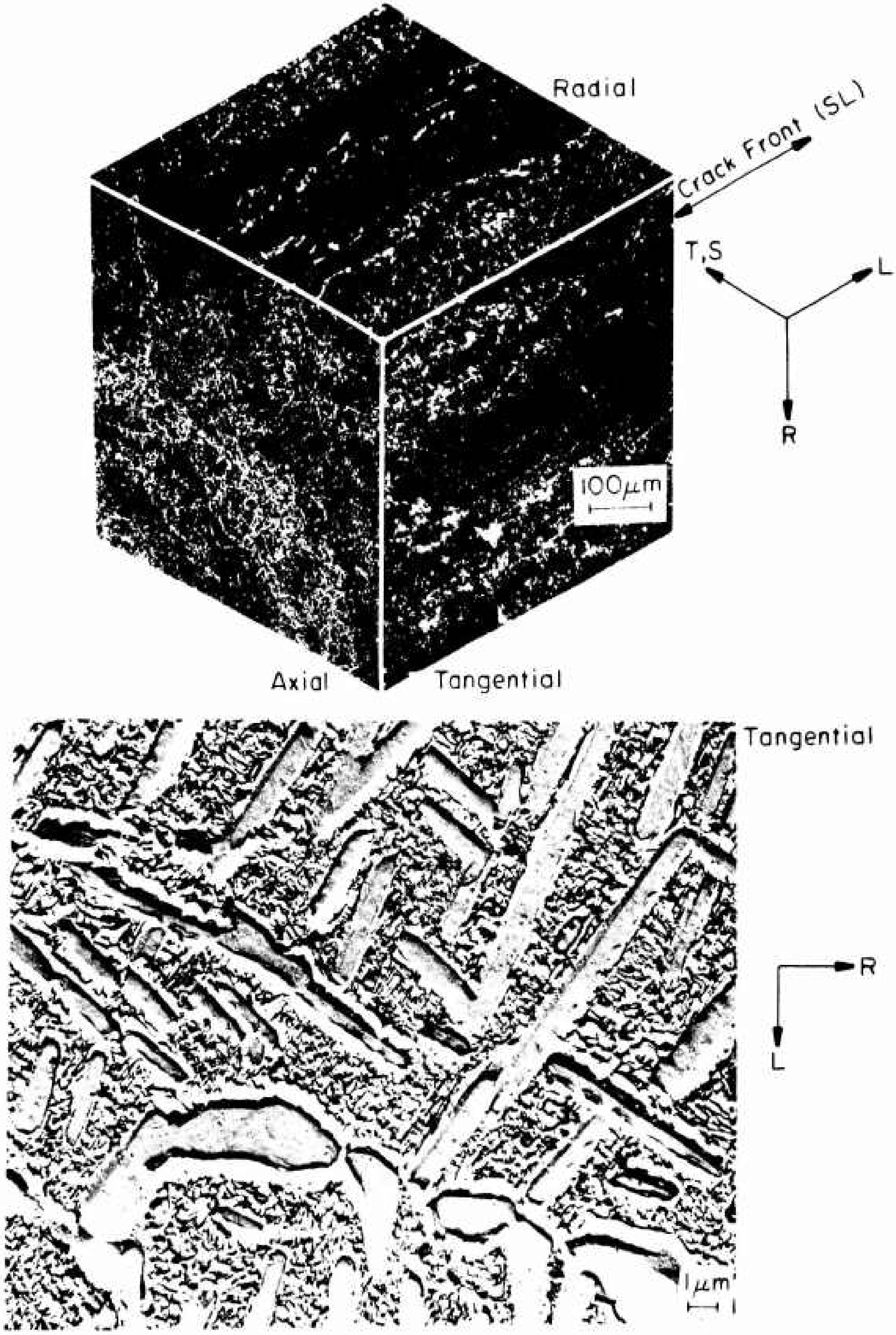
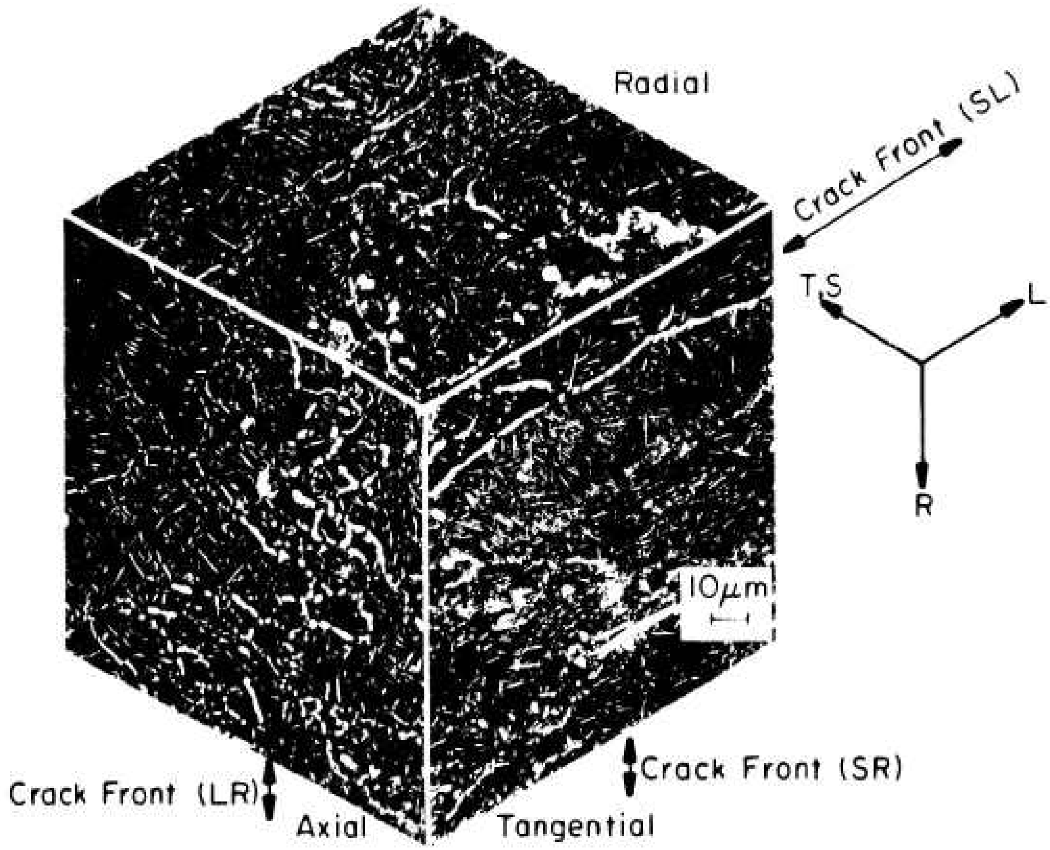


Figure 177. Alloy 227(7Mo-4Cr-2.5Al). Six inch billet full piece, center samples 7SLC1 and 7LRC2 (Table LXVII). Solution annealed 1450F-2 hr WQ plus 1350F-8 hr WQ, aged 925F-8 hr. Isometric X100, surface replica X5200.

YS(ksi):	151 (L)	RA(%):	36 (L)	K_Q(ksi$\sqrt{\text{in}}$):	84 (LR)
	152 (T)		18 (T)		50 (SL)



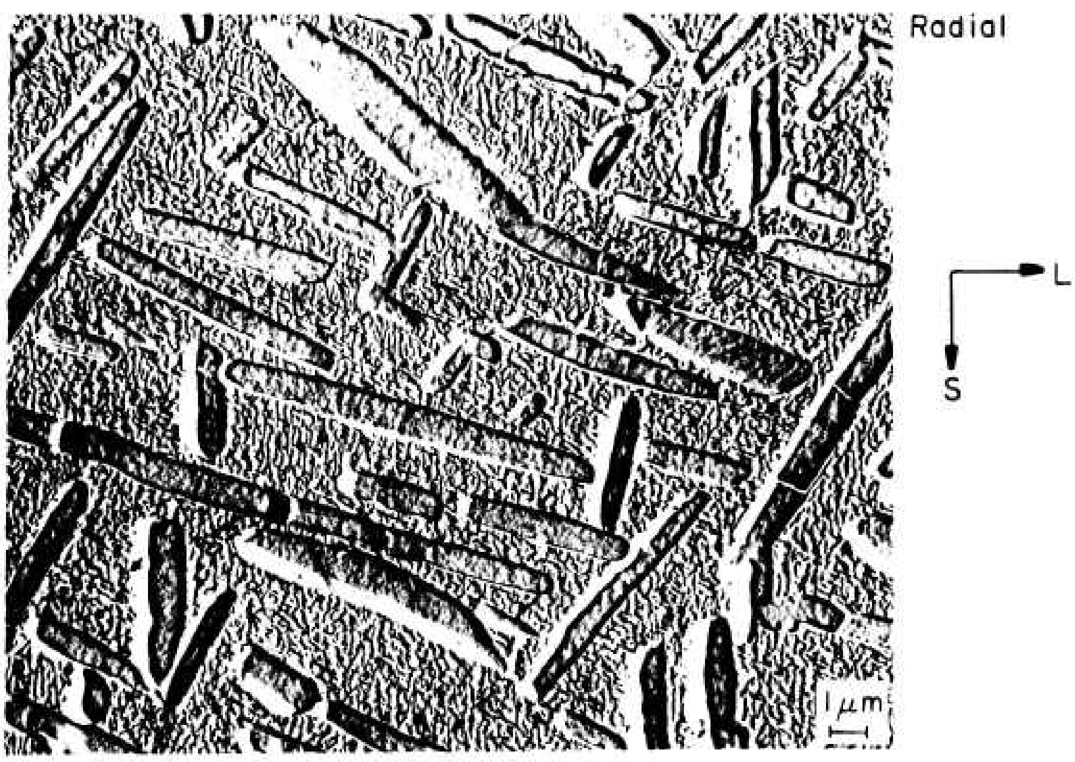


Figure 178. Alloy 227, sample 7SLC1. Isometric X500, surface replica X5200.

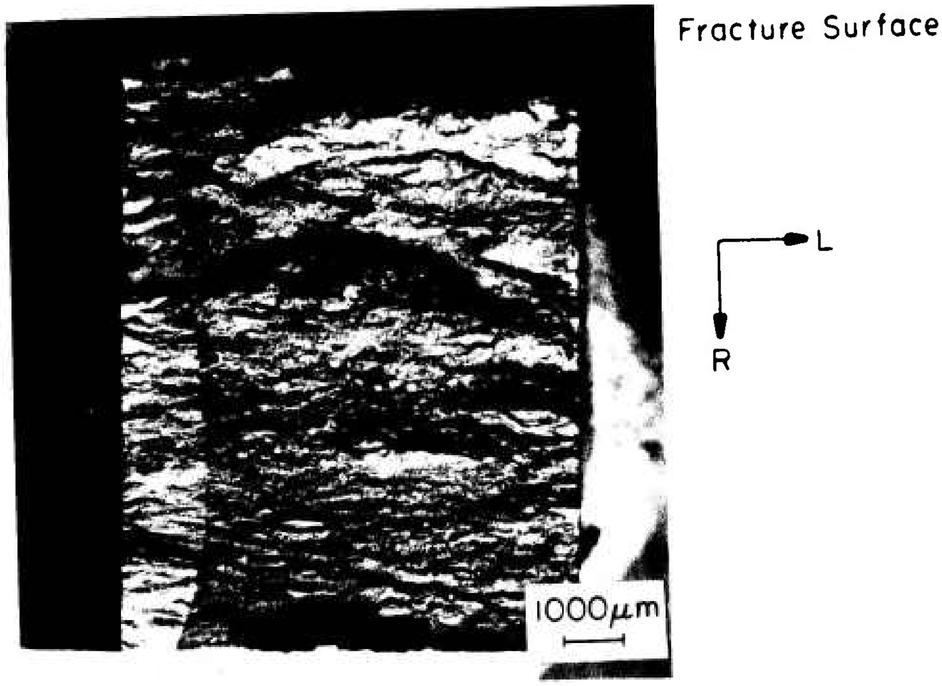


Figure 179. Alloy 227, sample 7SLC1. Fracture surface X8.

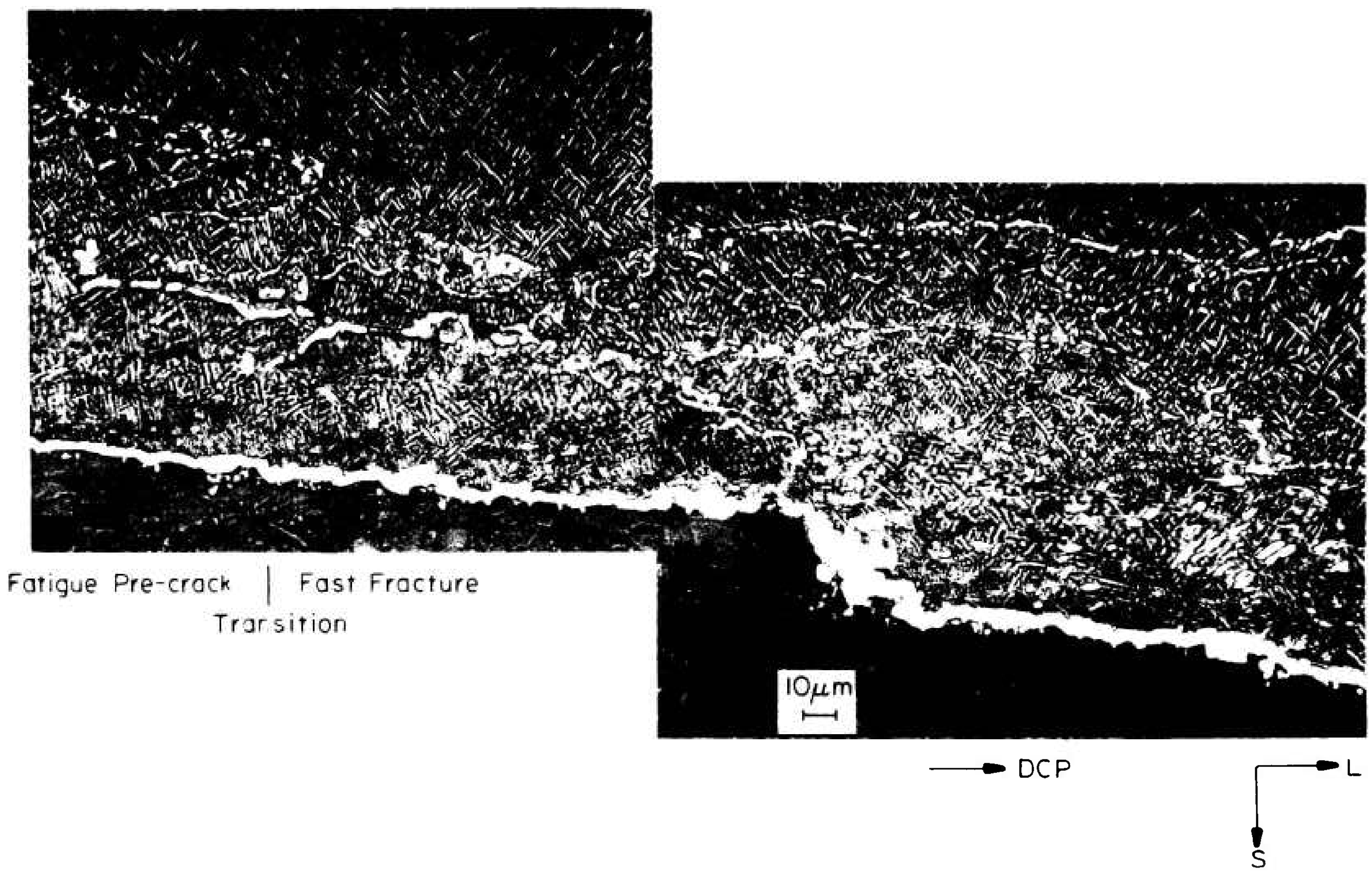


Figure 180. Alloy 227, sample 7SLC1. Crack path X500.

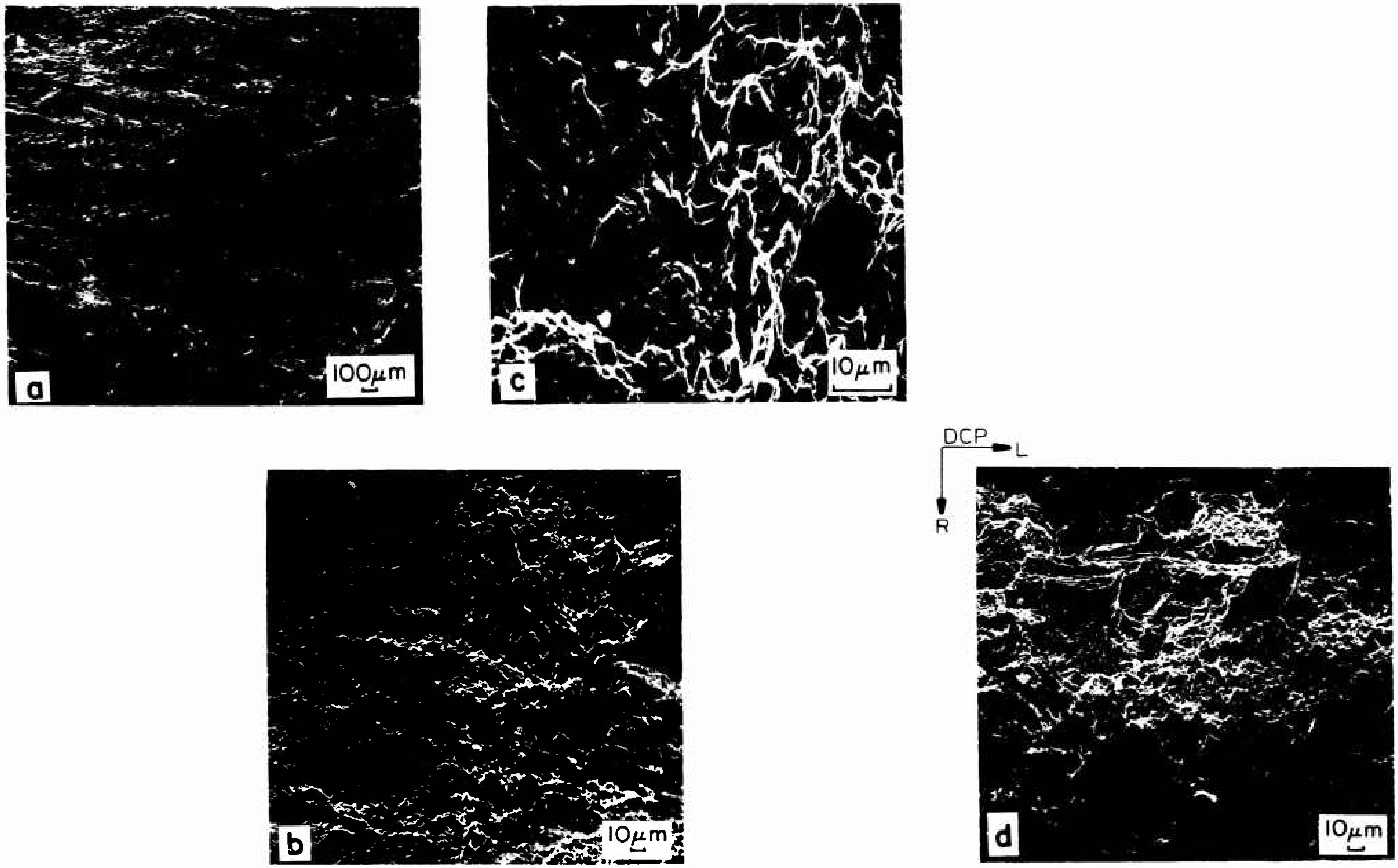
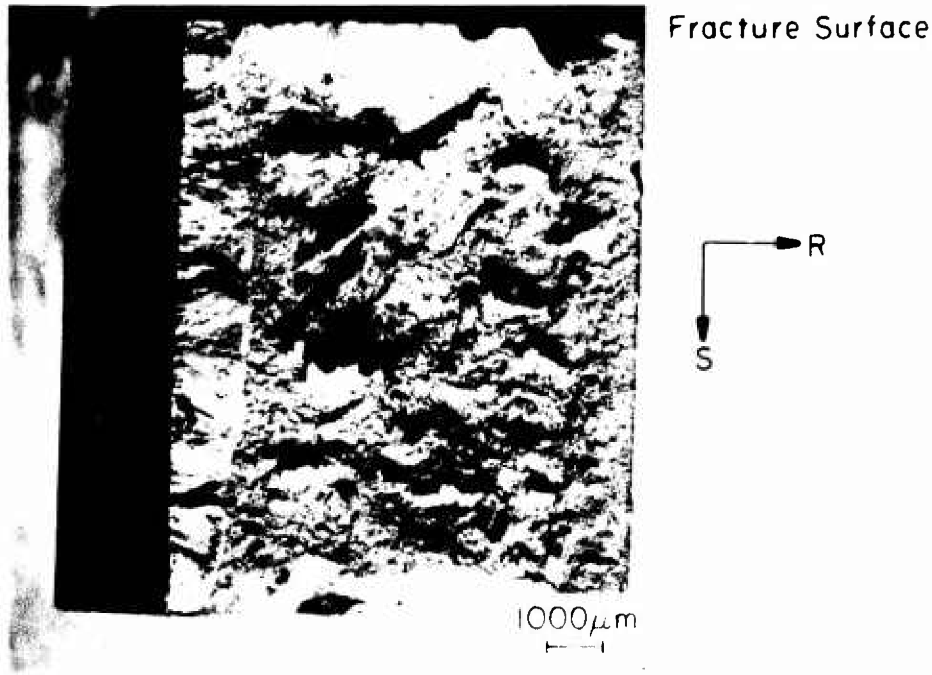


Figure 181. Alloy 227, sample 7SLC1. SEM of fracture surface (a) X25, (b) X250 - precrack/fast fracture transition, (c) X1000 - fast fracture close to transition, (d) X250 - fast fracture.



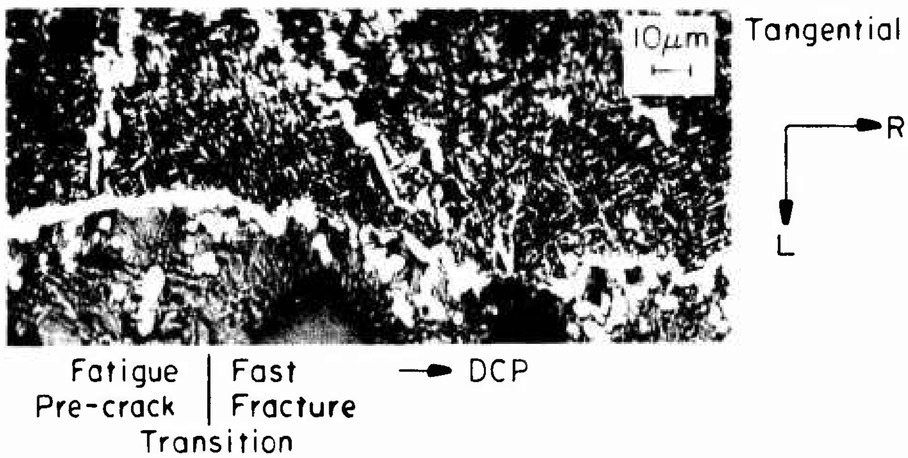


Figure 182. Alloy 227, sample 7LRC2. Fracture surface X8, crack path X500.

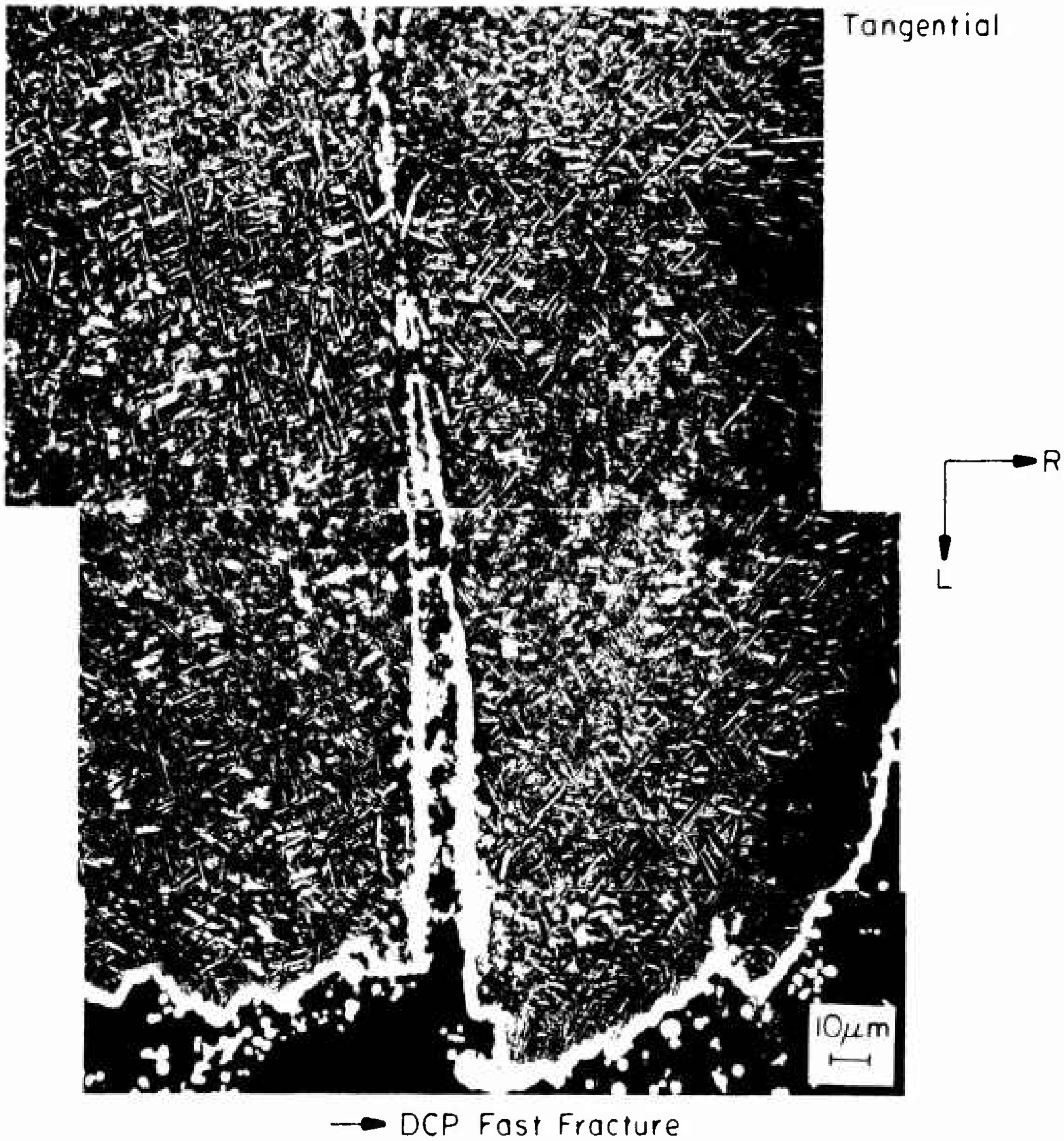


Figure 183. Alloy 227, sample 7LRC2. Crack path X500. Note extended branch crack (vertical) with apparent voids ahead of crack tip.

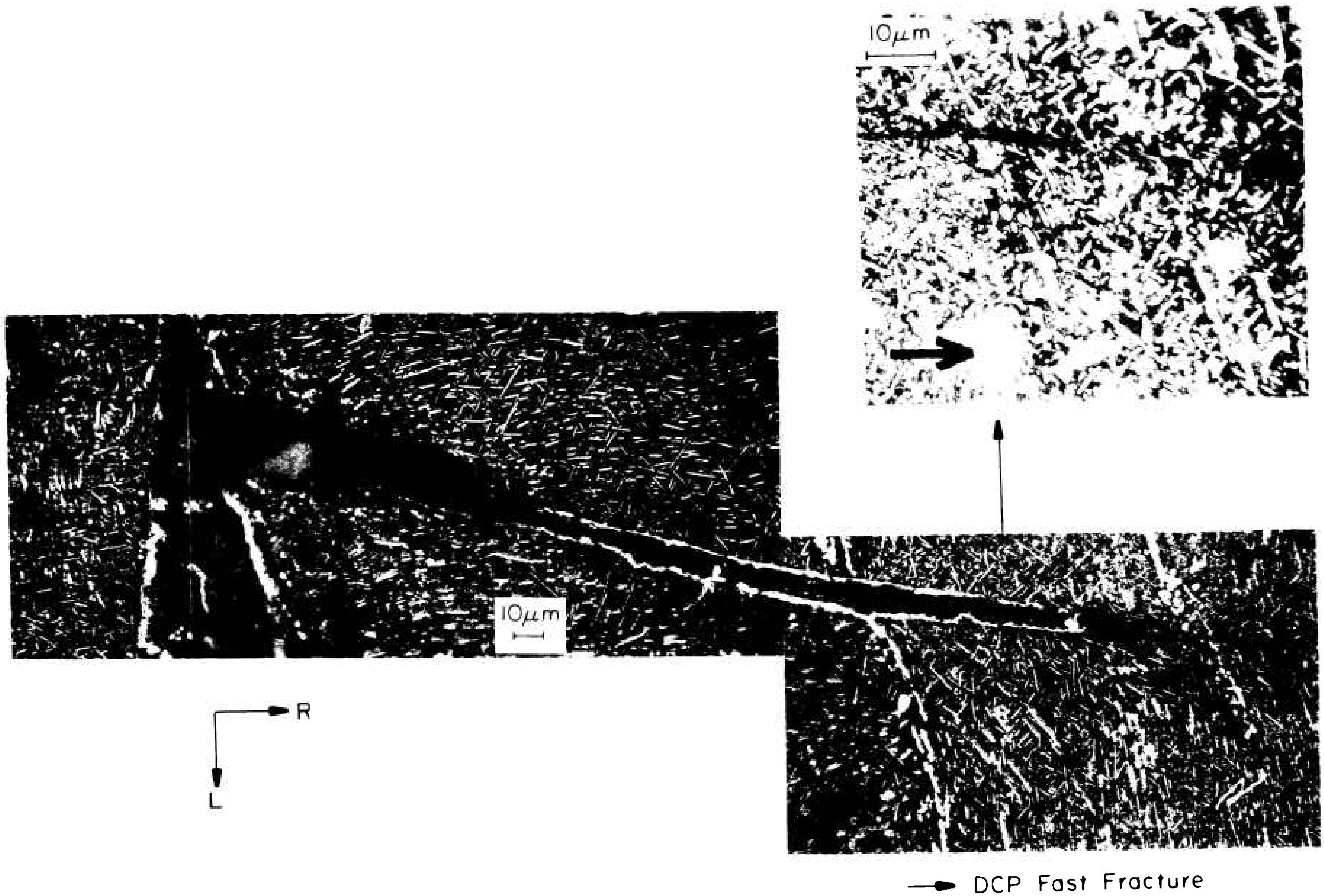


Figure 184. Alloy 227, sample 7LRC2. Crack path X500 (bottom), X1200 (top). Note apparent void (below) and deformed material (ahead) in vicinity of crack tip.

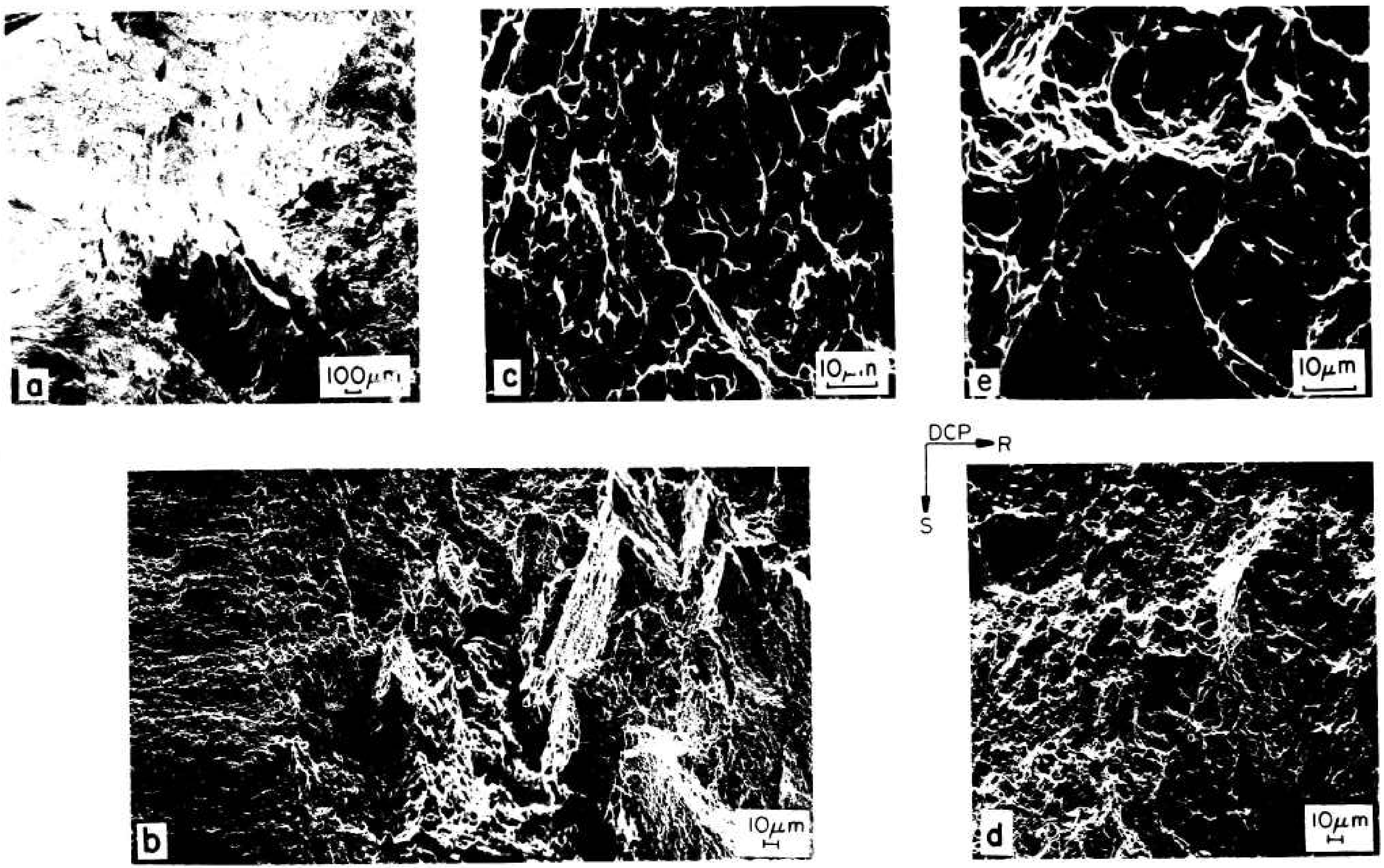
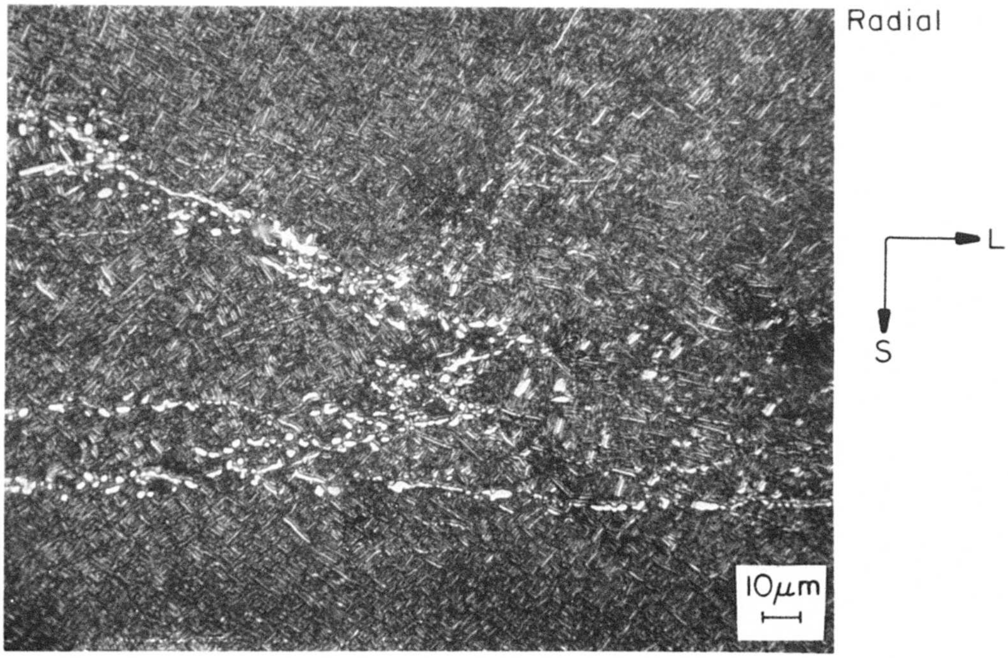


Figure 185. Alloy 227, sample 7LRC2. SEM of fracture surface (a) X25, (b) X250 - precrack/ fast fracture transition, (c) X900 - fast fracture close to transition, (d) X250, (e) X1000 - fast fracture.



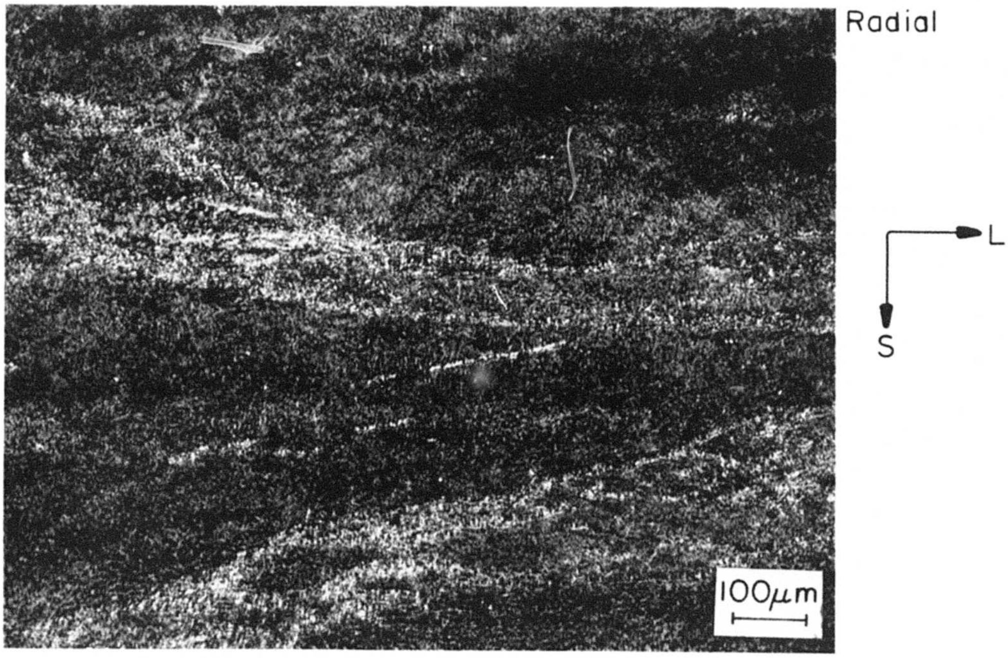


Figure 186. Alloy 227 (7Mo-4Cr-2.5Al). Six inch billet full piece, edge samples 7SLE2 and 7LRE2 (Table LXVII). Solution annealed 1450F - 2 hr WQ + 1350F - 8 hr WQ, aged 925F - 8 hr. Radial face X500 (top), X100 (bottom).

YS (ksi):	164 (L)	RA (%):	40 (L)	K (ksi$\sqrt{in.}$):	62 (LR)
	163 (T)		10 (T)		44 (SL)

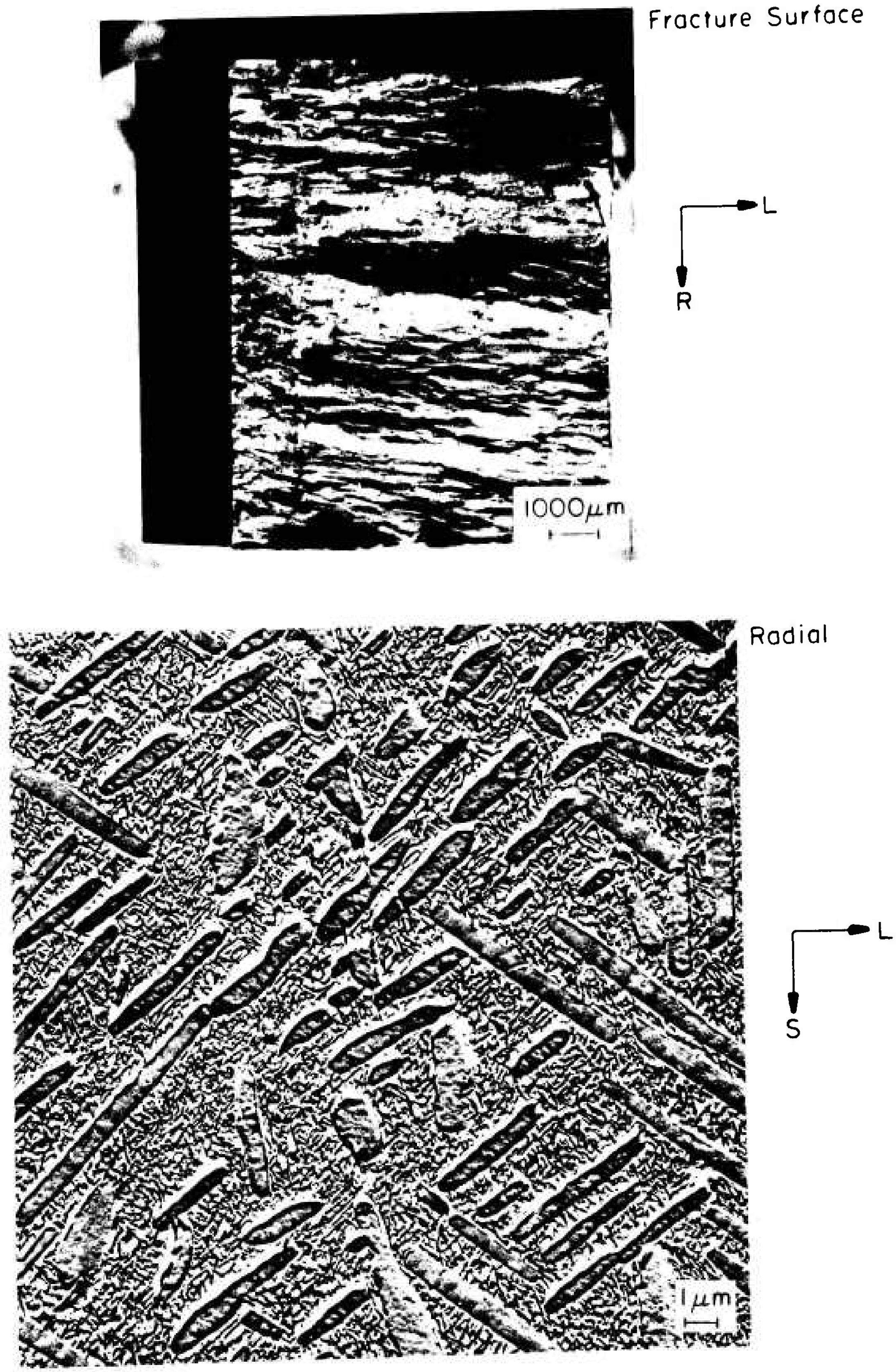


Figure 187. Alloy 227, sample 7SLE2. Fracture surface X8, surface replica X5200.

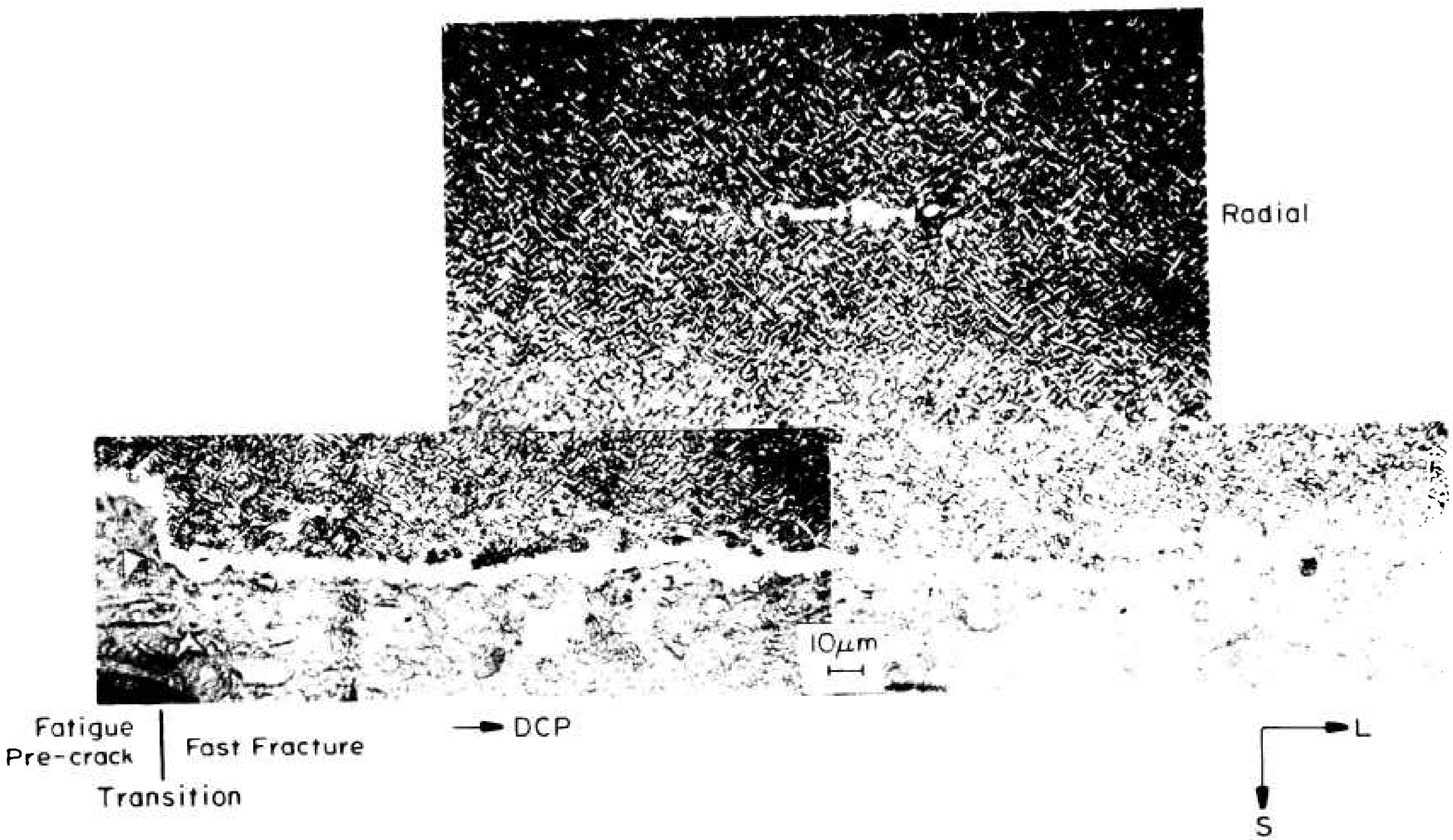


Figure 188 . Alloy 227, sample 7SLE2. Crack path X500.

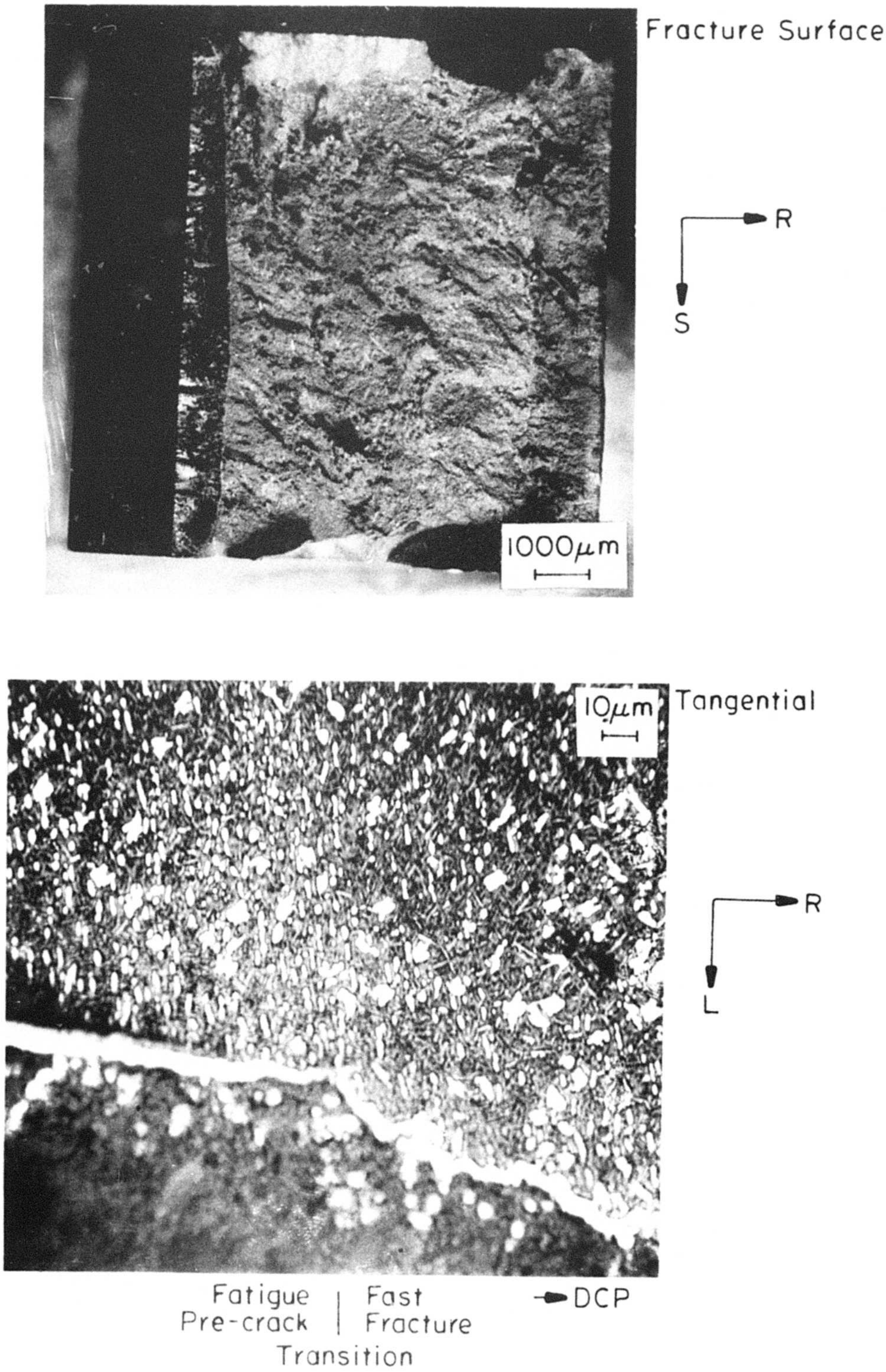


Figure 189 . Alloy 227, sample 7LRE2. Fracture surface X8, crack path X500.

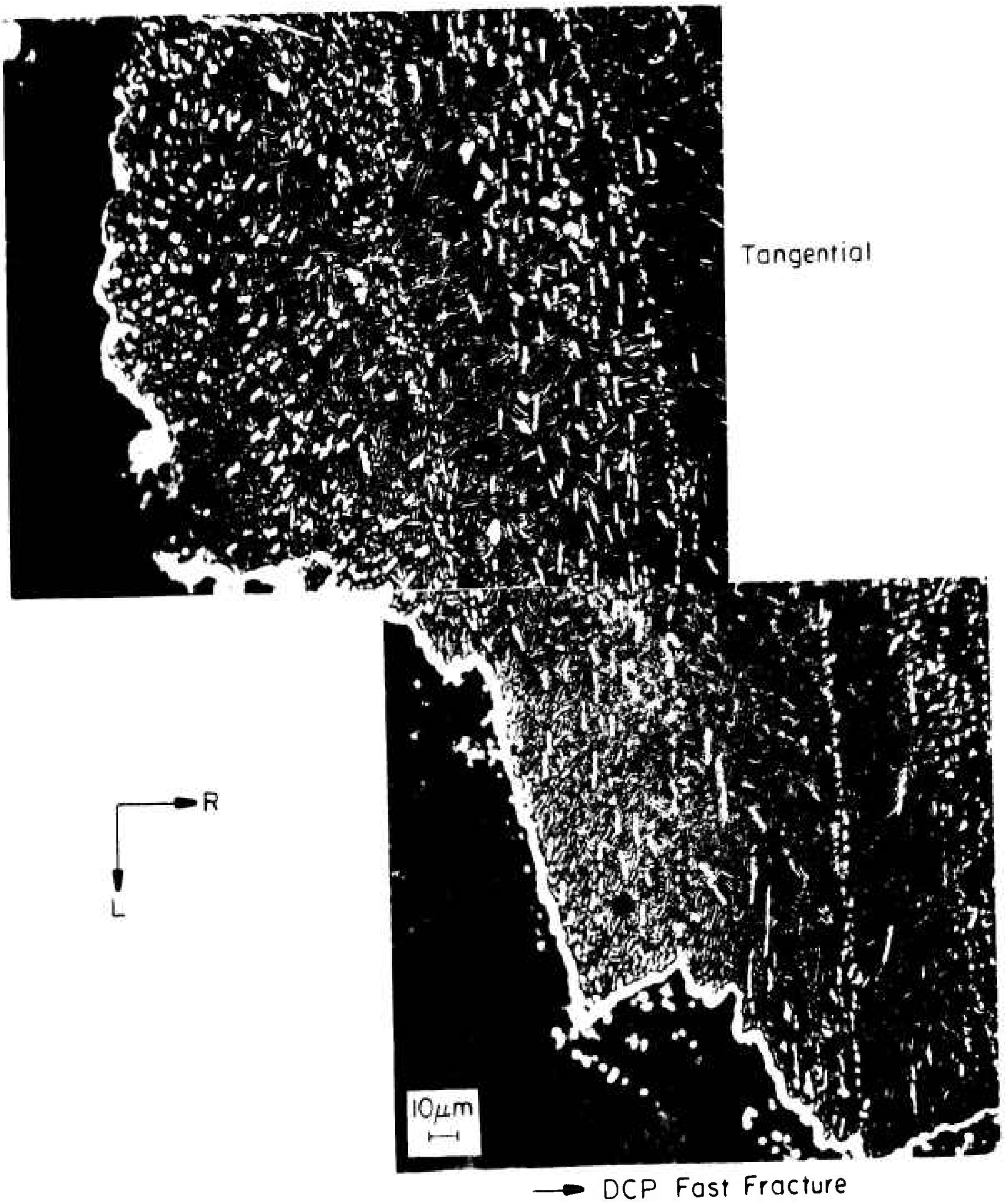


Figure 190. Alloy 227, sample 7LRE2. Crack path X500, note large deviation following alpha particles.

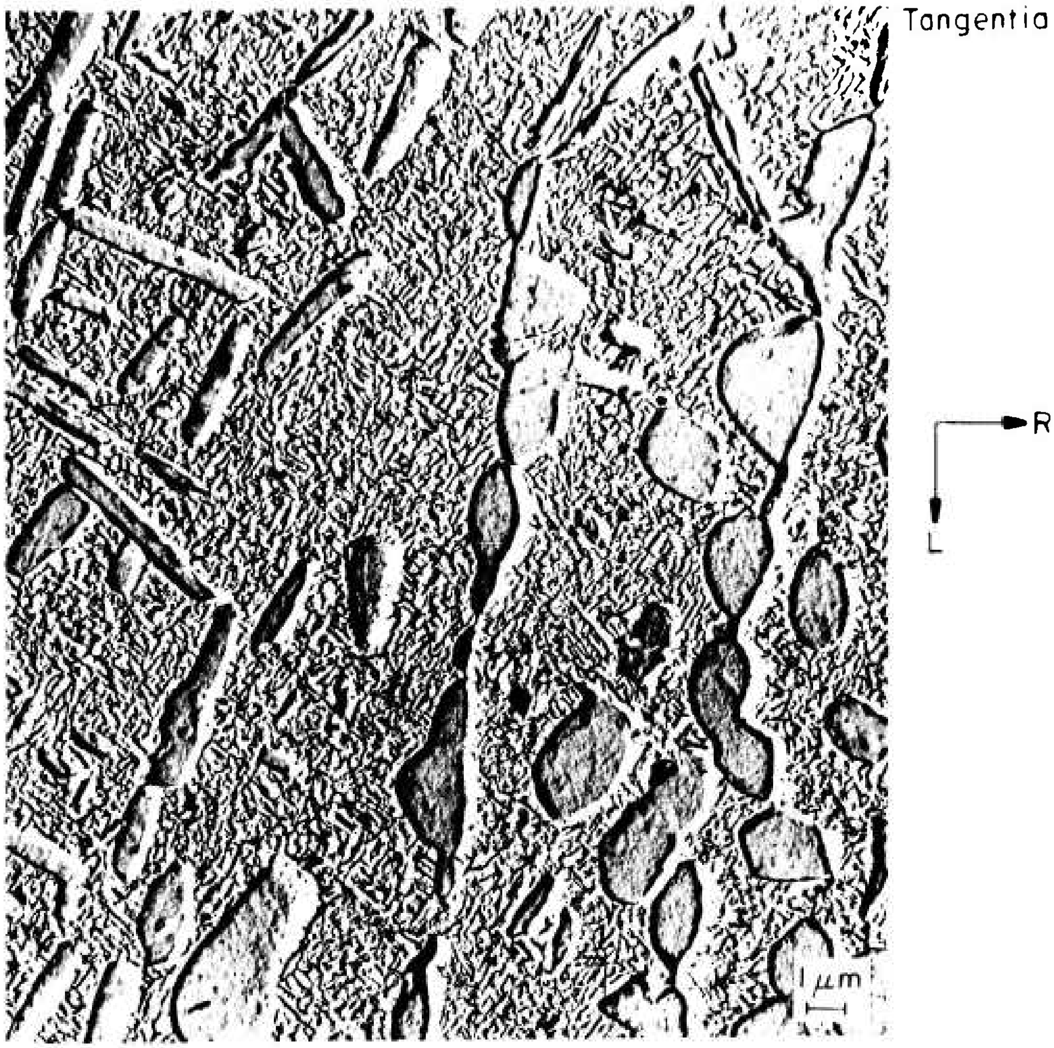


Figure 191. Alloy 227, sample 7LRE2. Surface replica. X5200

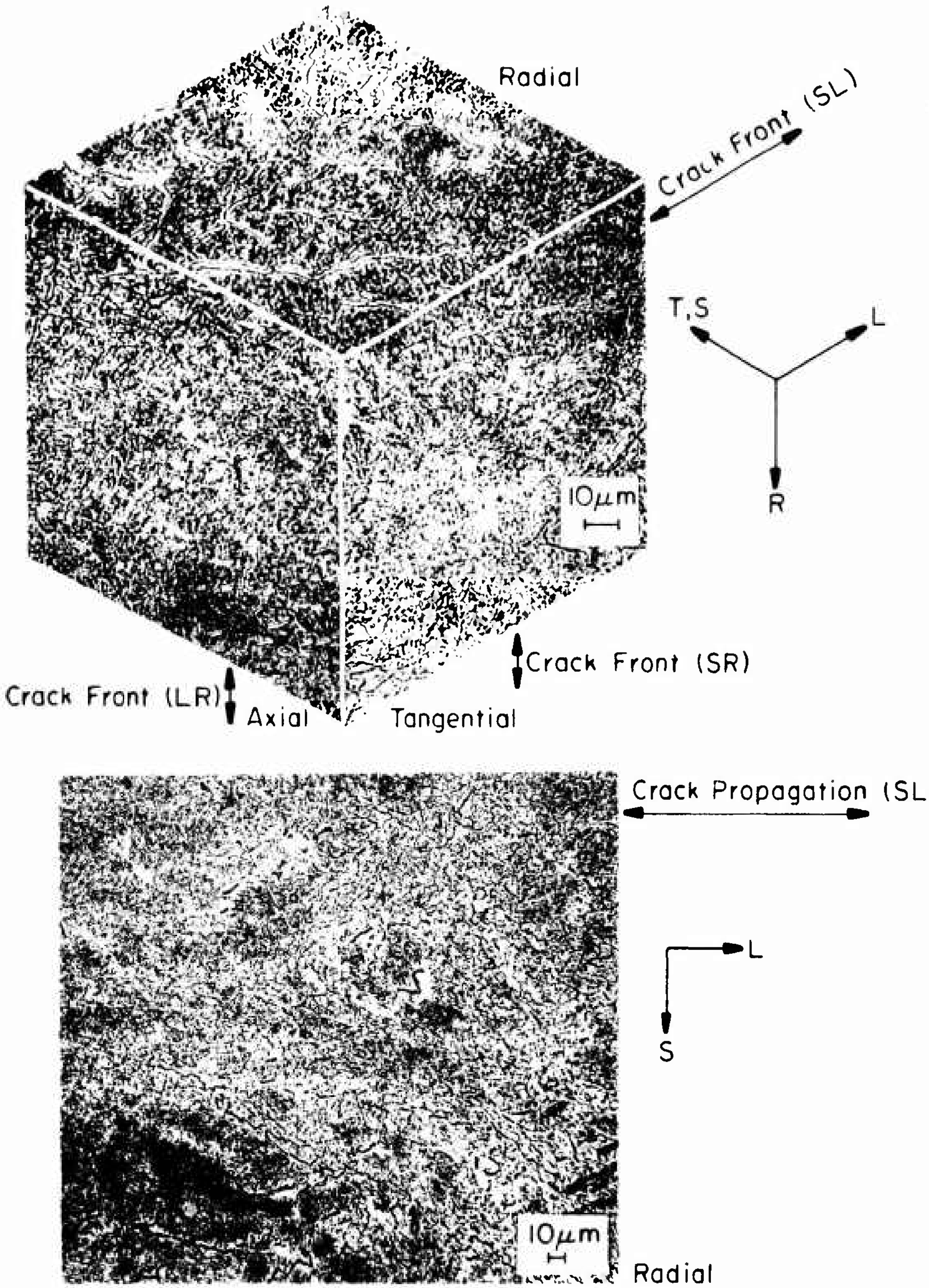


Figure 192. Alloy 253 (10Mo-8V-2.5Al). Six inch billet full piece center samples 3SLC2 and 3LRC1 (Table LXVIII). Solution annealed 1350F - 4 hr. WQ + 1225F - 2 hr WQ, aged 900F - 96 hr. isometric X500, radial face X250.

YS (ksi):	143 (L)	RA (%):	52 (L)	K_Q(ksi√):	123 (LR)
	147 (T)		19 (T)		76 (SL)

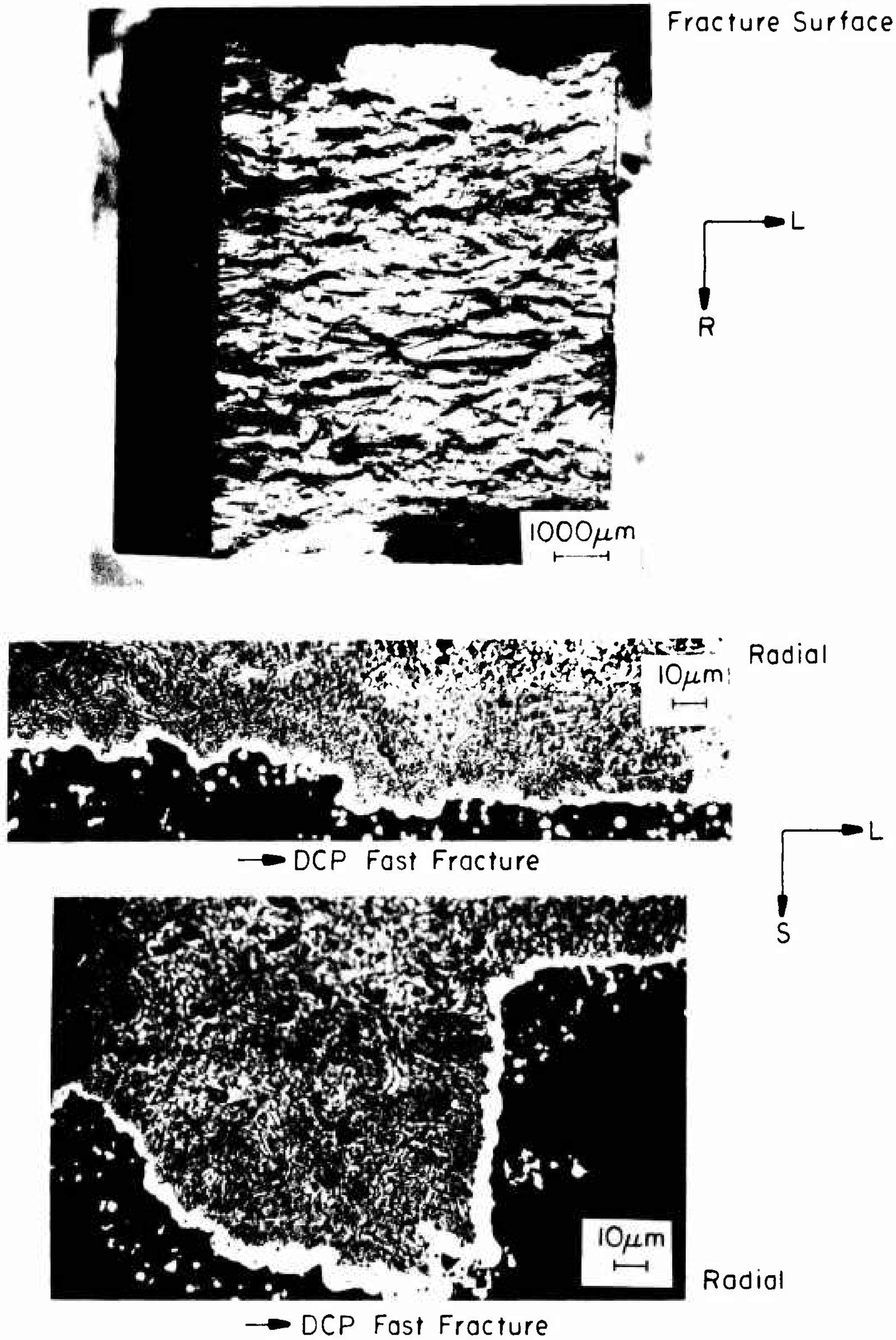


Figure 193. Alloy 253, sample 3SLC2. Fracture surface X8, crack path (top) X500 close to transition, (bottom) X500 distant from transition.

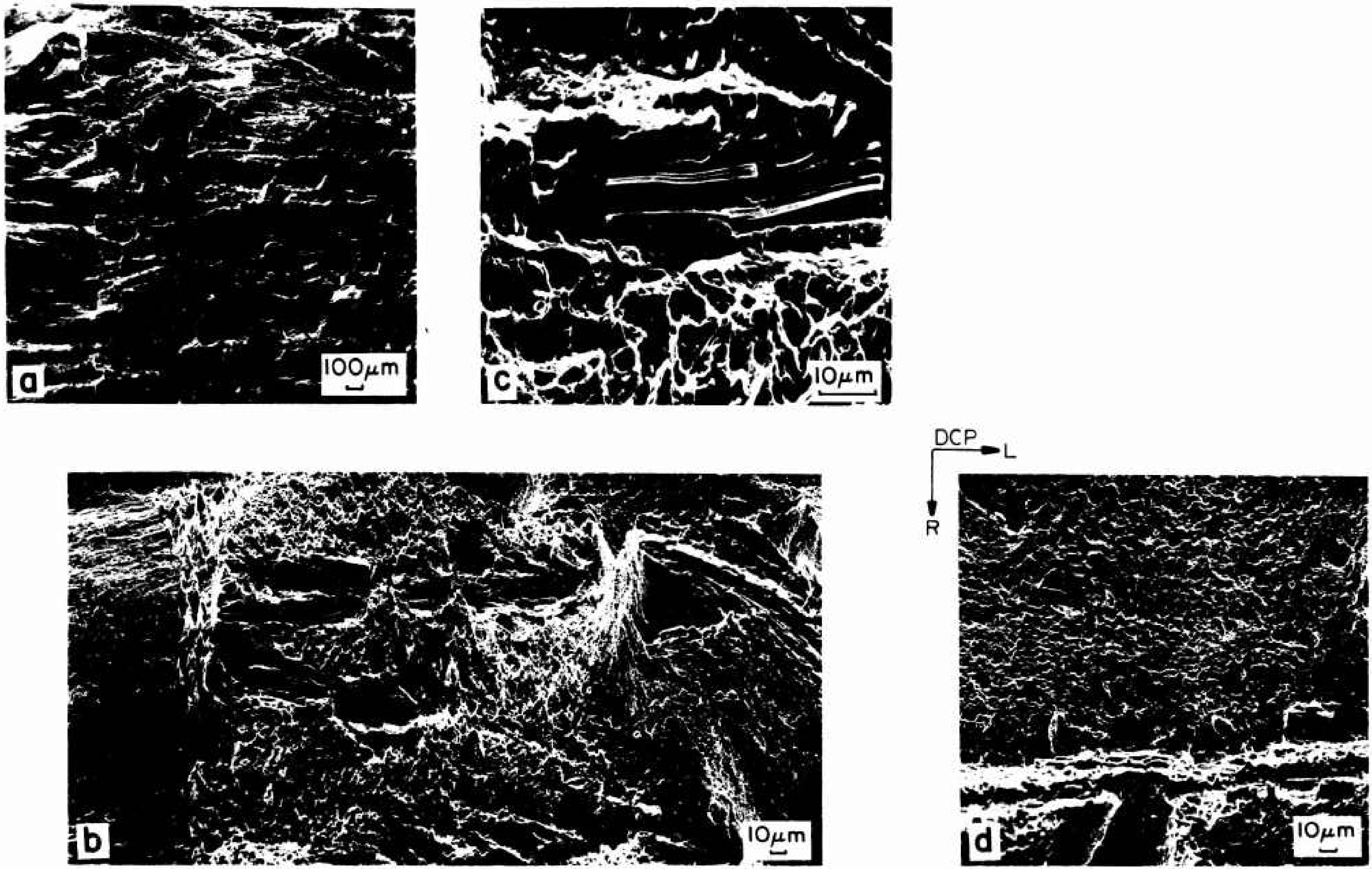


Figure 194. Alloy 253, sample 3SLC2. SEM of fracture surface (a) X25, (b) X250 - precrack/fast fracture transition, (c) X1000 - fast fracture close to transition, (d) X300 - fast fracture.

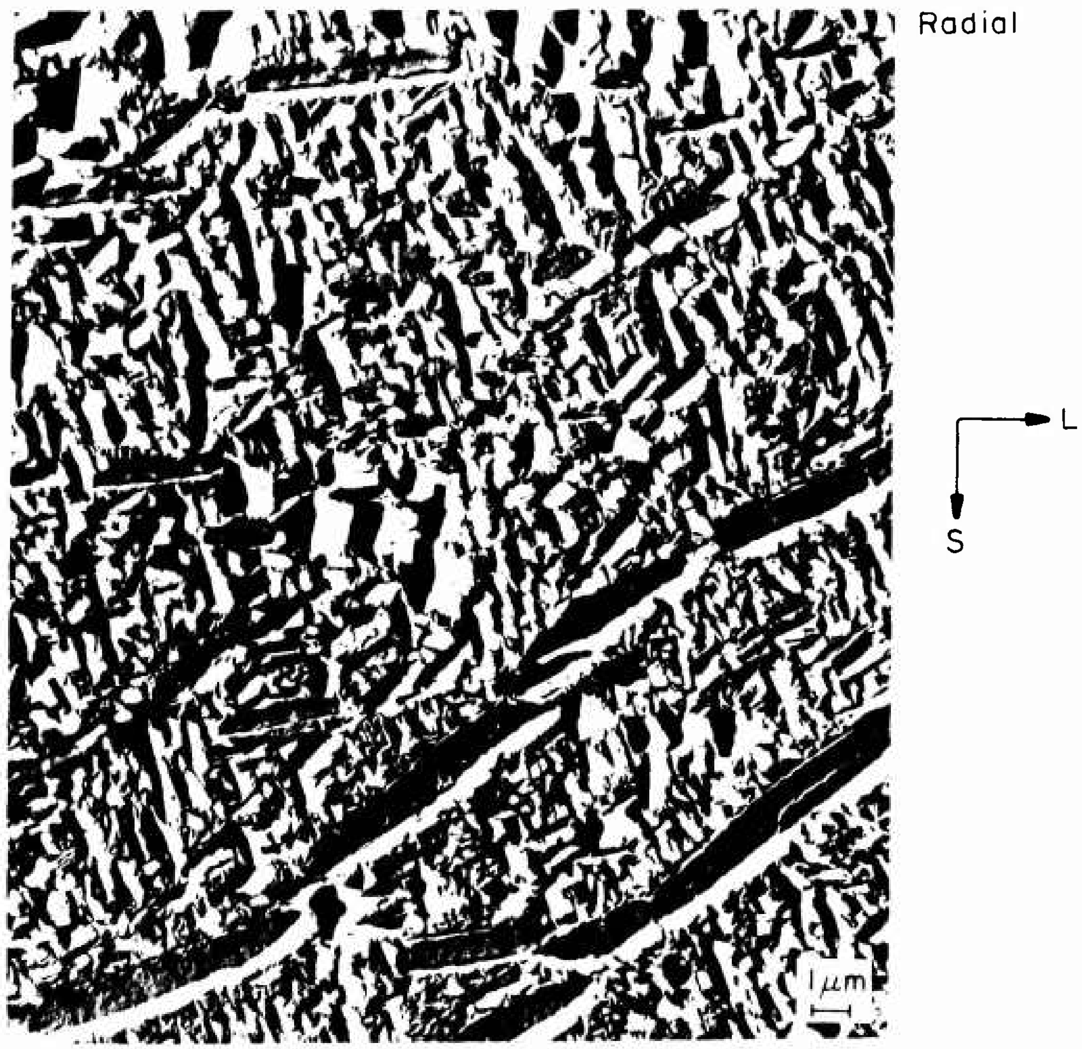
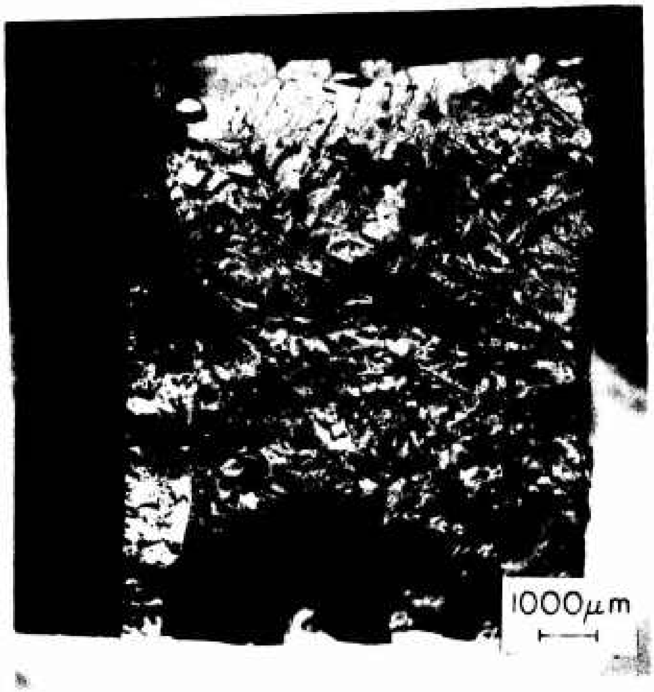


Figure 195. Alloy 253, sample 3SLC2. Surface replica X5200.



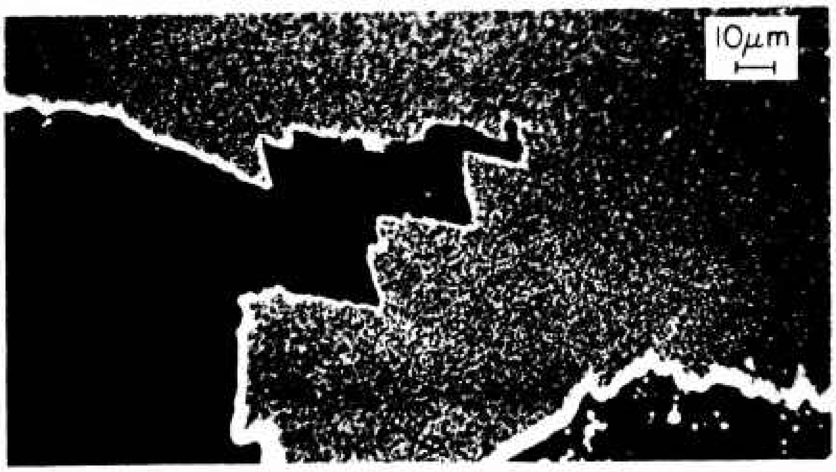


Figure 196. Alloy 253, sample 3LRC1. Fracture surface X8, crack path X500. Note path deviation.

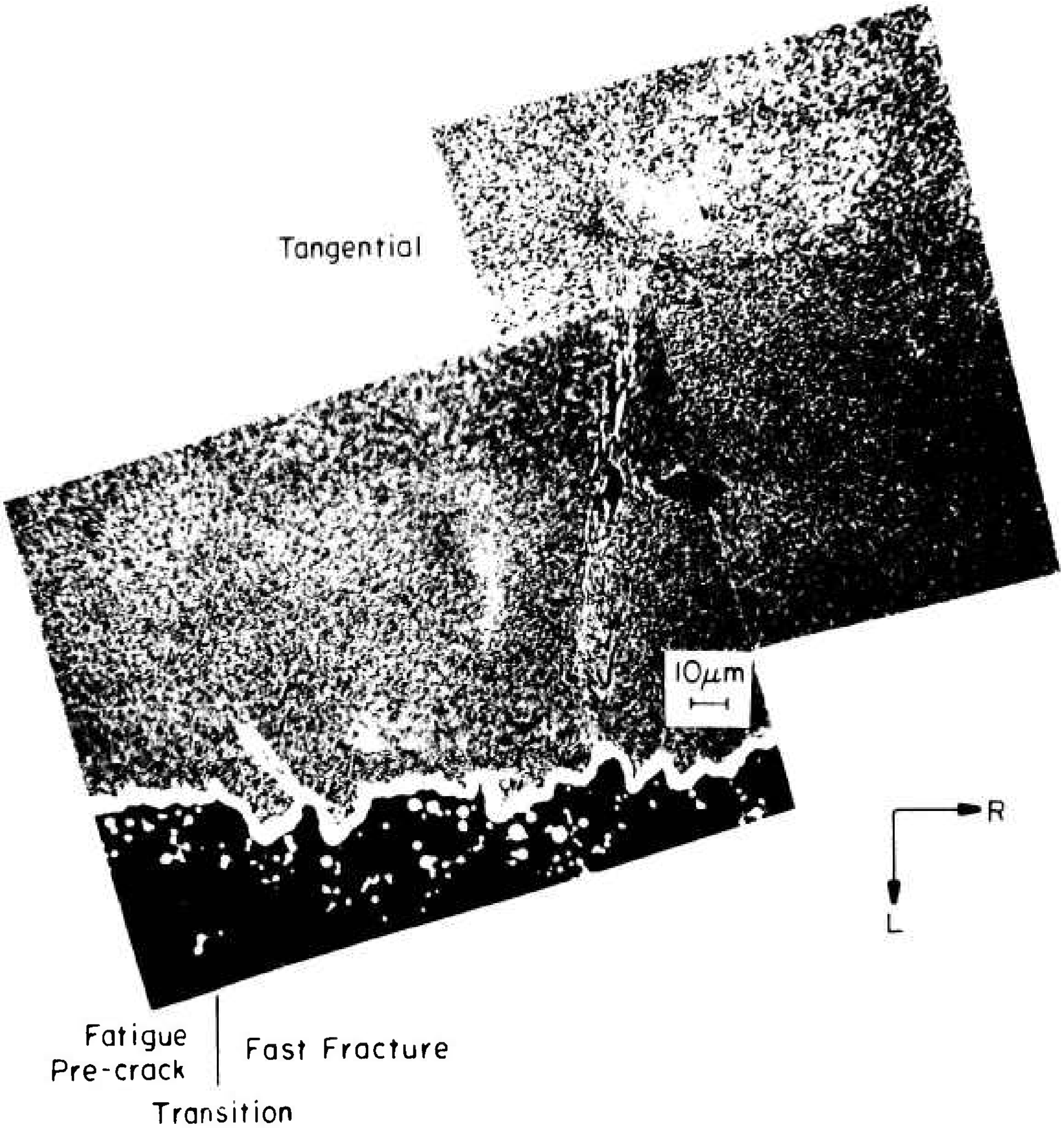


Figure 197. Alloy 253, sample 3LRC1. Crack path X5C0.

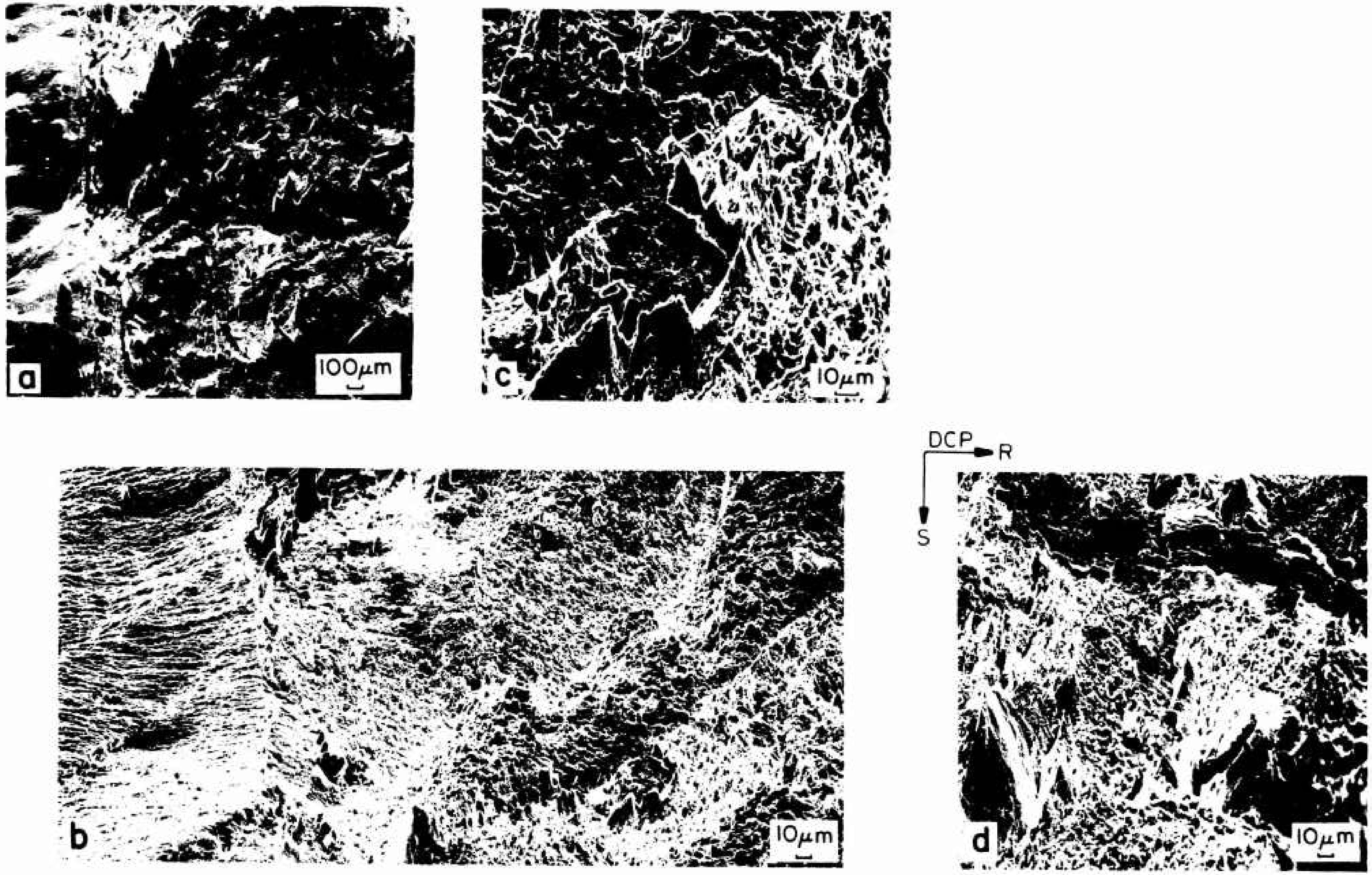


Figure 198 .Alloy 253, sample 3LRC1. SEM of fracture surface (a) X25, (b) X250 - precrack/fast fracture transition, (c) X500 - fast fracture close to transition, (d) X250 - fast fracture.

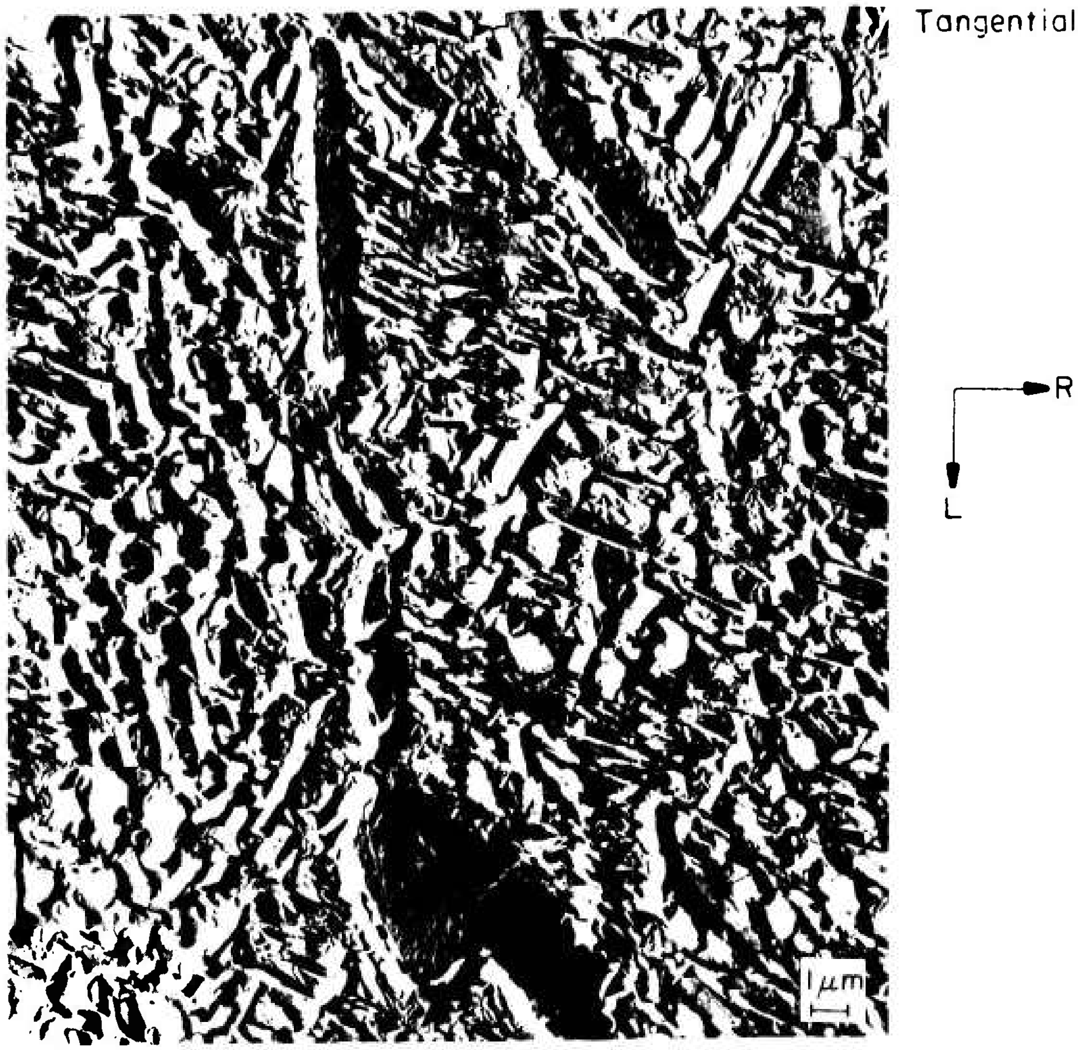
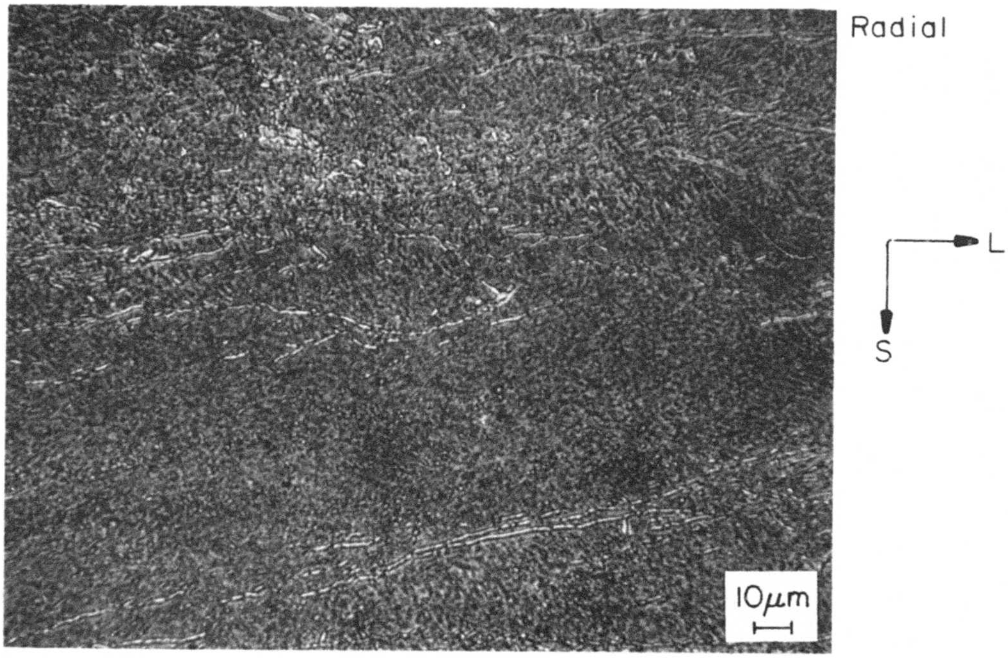


Figure 199 . Alloy 253, sample 3LRC1. Surface replica. X5200



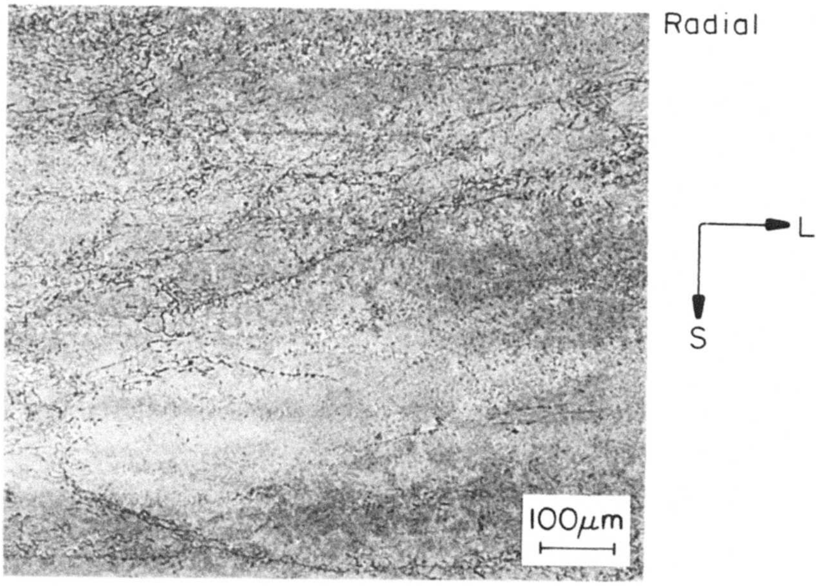


Figure 200. Alloy 253(10Mo-6Cr-2.5Al). Six inch billet full piece, edge samples 3SLE2 and 3LRE2 (Table LXVIII). Solution annealed 1350F - 4 hr WQ plus 1225F-2 hr WQ, aged 900F-96 hr. Radial face X500 (top), X100 (bottom).

YS(ksi):	150 (L)	RA(%):	51 (L)	K_Q(ksi√in):	137 (LR)
	147 (T)		18 (T)		81 (SL)

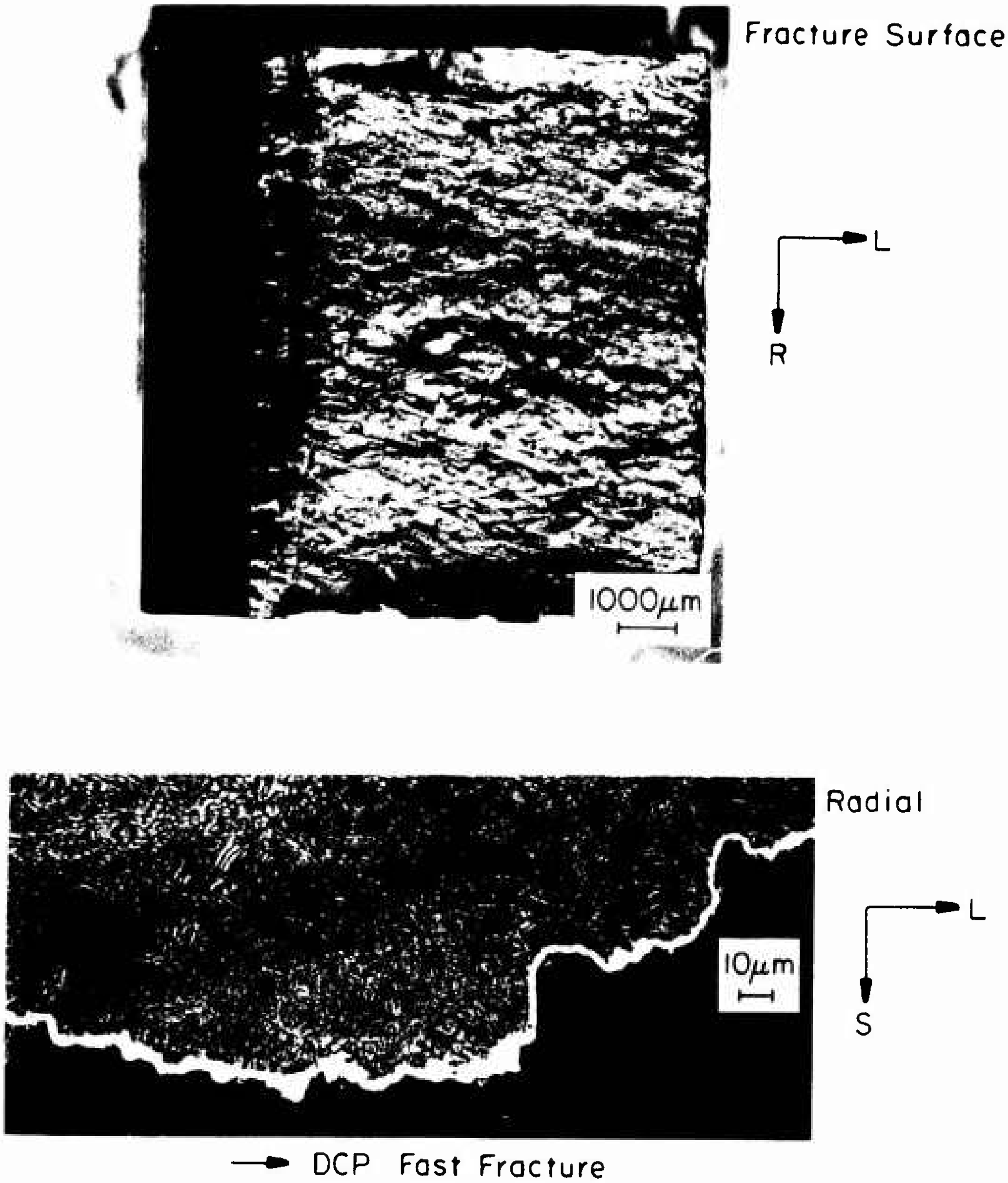


Figure 201. Alloy 253, sample 3SLE2. Fracture surface X8, crack path X500.

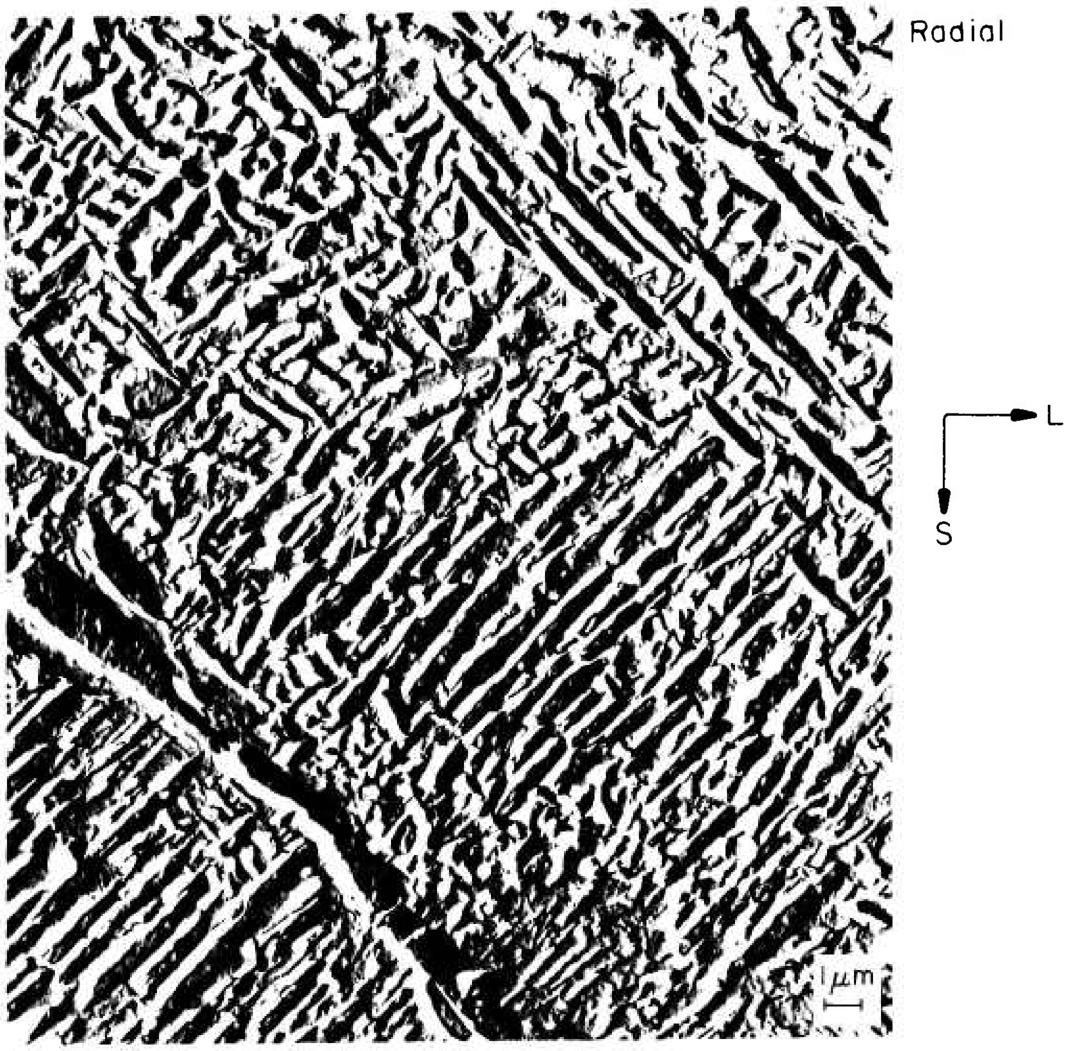


Figure 202. Alloy 253, sample 3SLE2. Surface replica X5200.

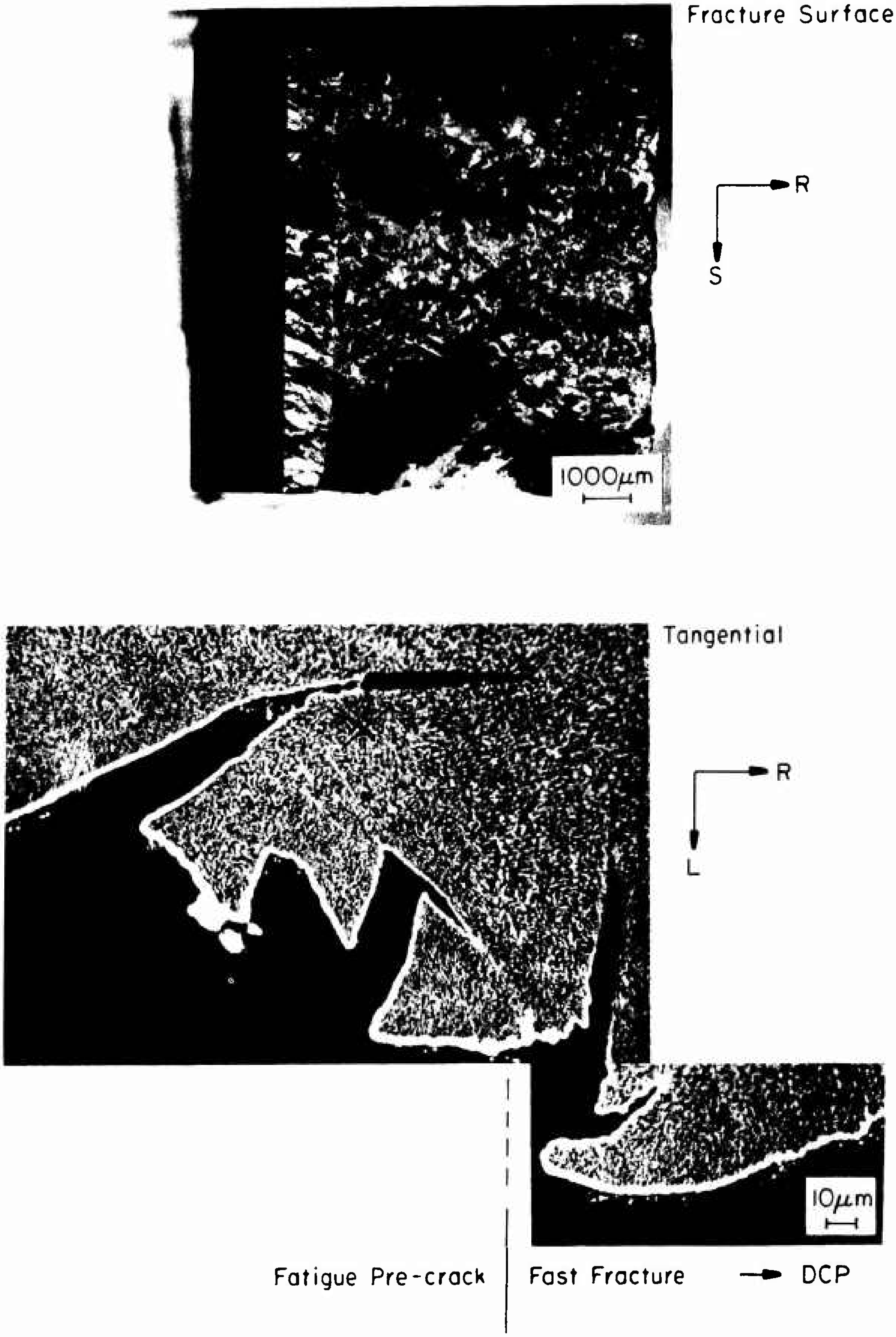


Figure 203. Alloy 253, sample 3LRE2. Fracture surface X8, crack path X500.

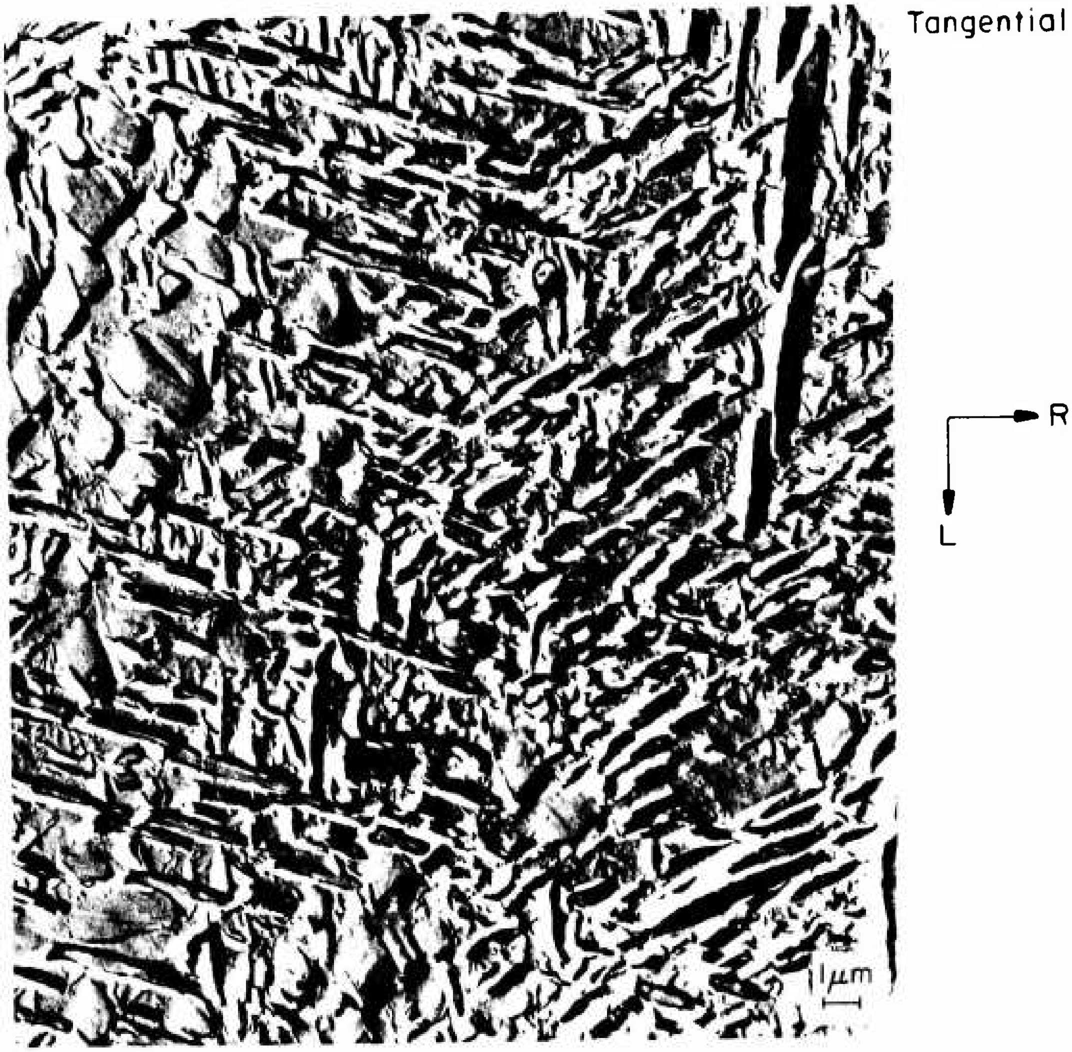
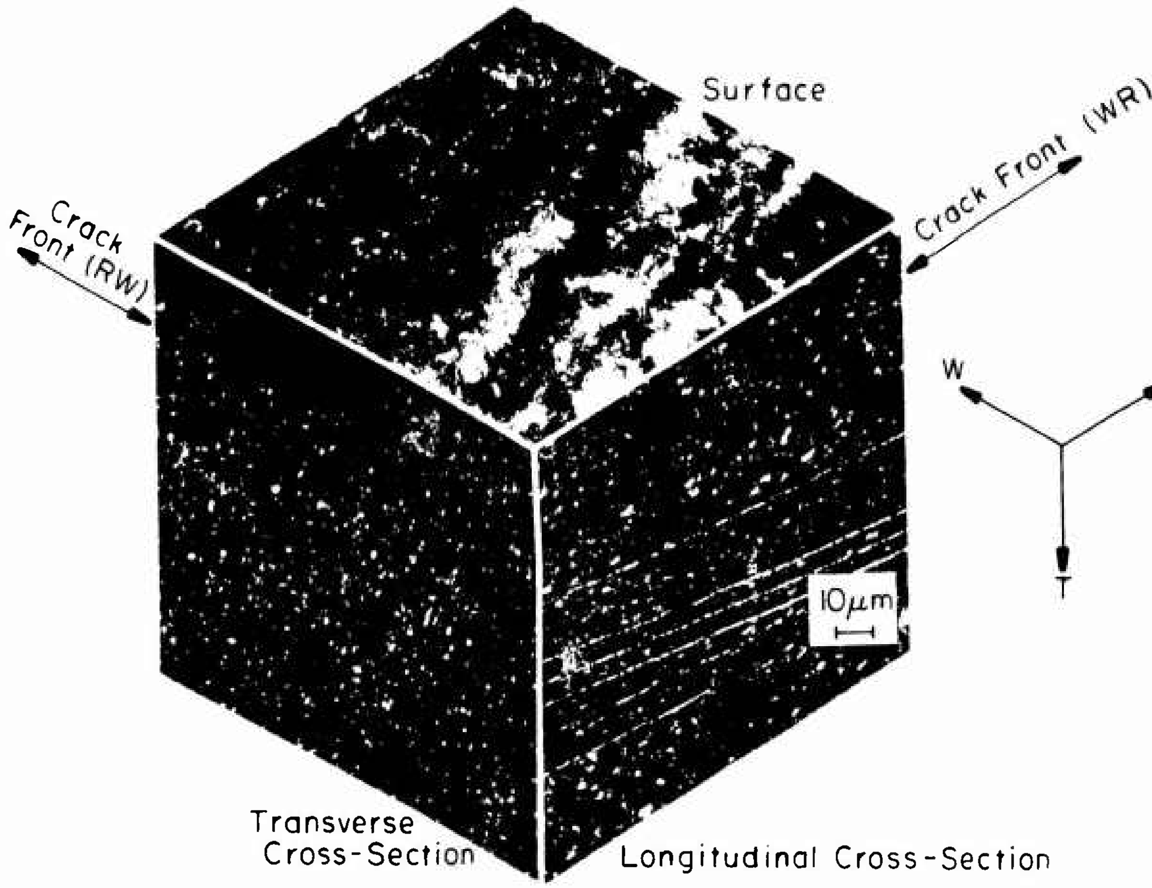


Figure 204. Alloy 253, sample 3LRE2. Surface replica X5200.



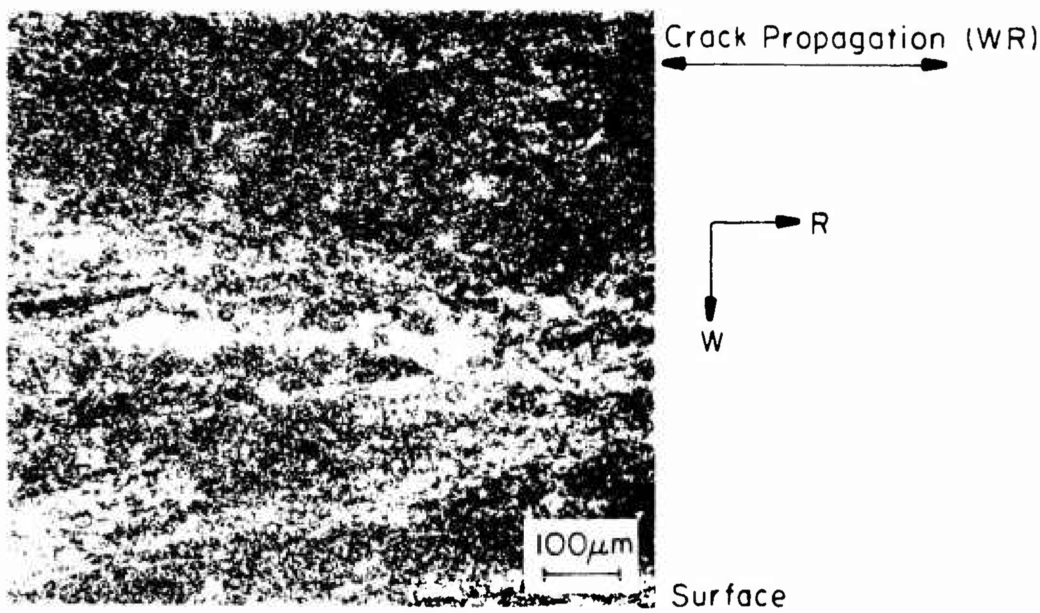
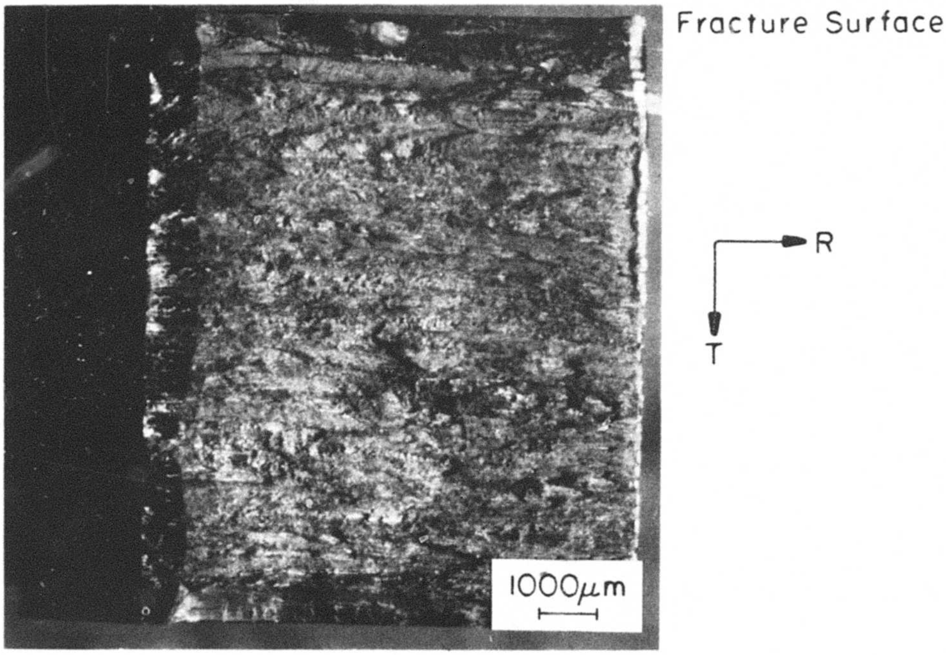


Figure 205. Alloy 334(10Mo-6Cr-2.5Al). Half inch plate, sample 4WRH1 (Table LXXVII). Solution annealed 1350F-8 hr WQ, aged 1025F-96 hr. Isometric X500, surface face X100.

YS(ksi):	159 (L)	RA(%):	36 (L)	K_Q(ksi$\sqrt{in}$):	65 (RW)
	171 (T)		9 (T)		60 (WR)



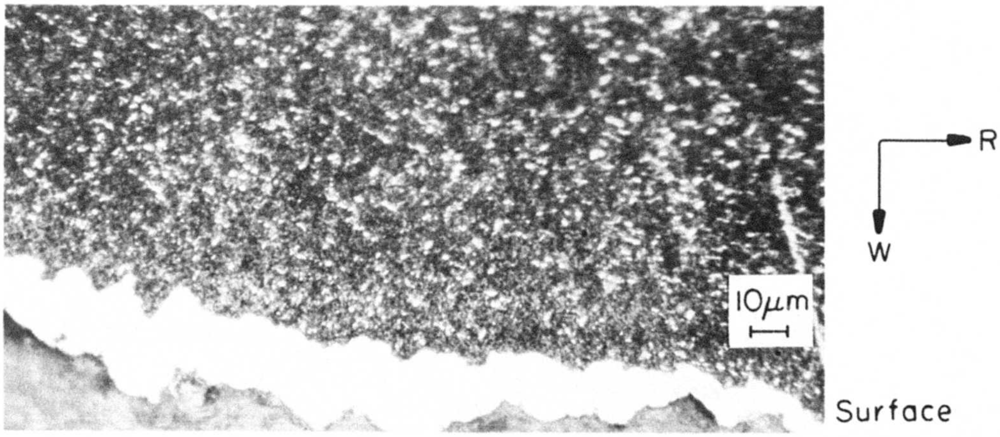


Figure 206. Alloy 334, sample 4WRH1. Fracture surface X8, crack path X500.

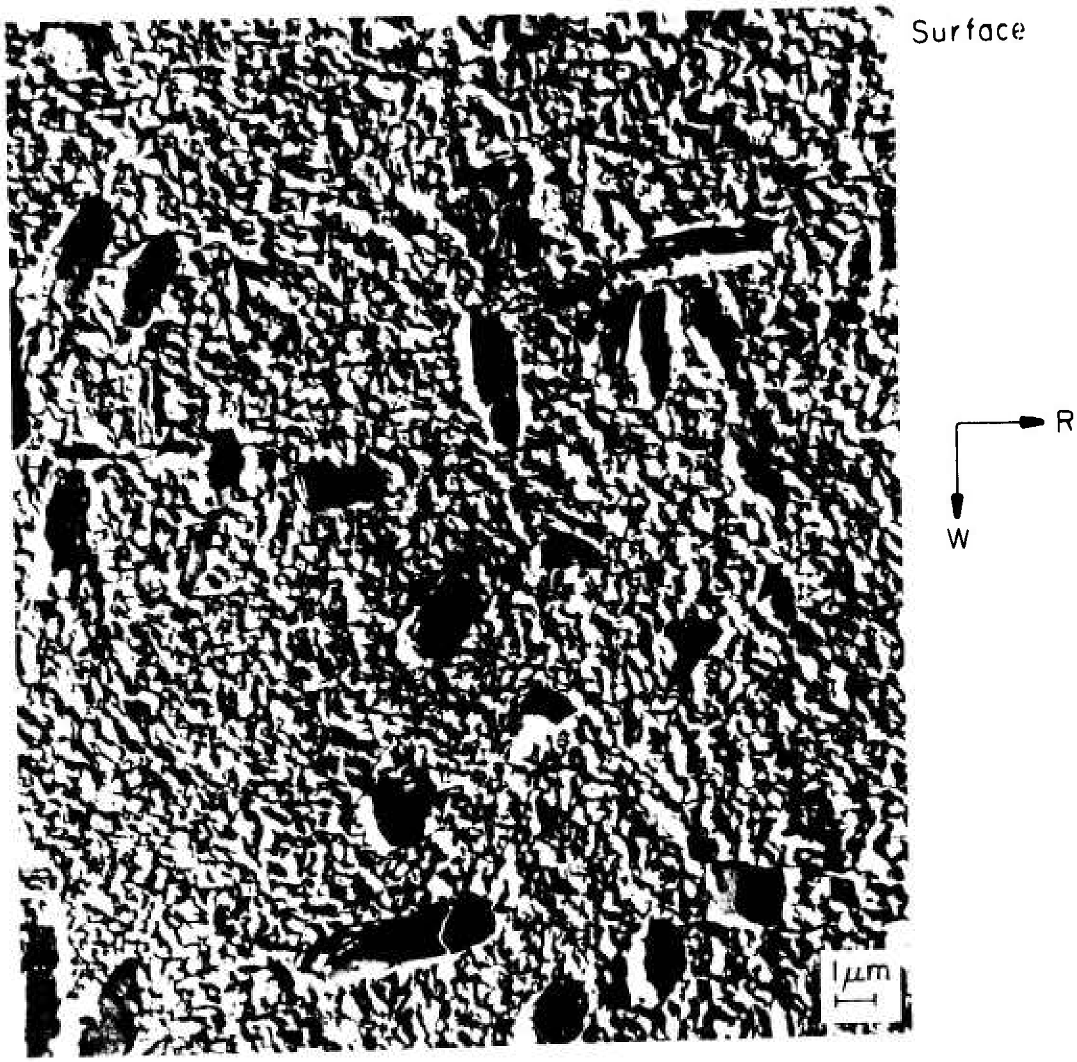


Figure 207. Alloy 334, sample 4WRH1. Surface replica X5200.

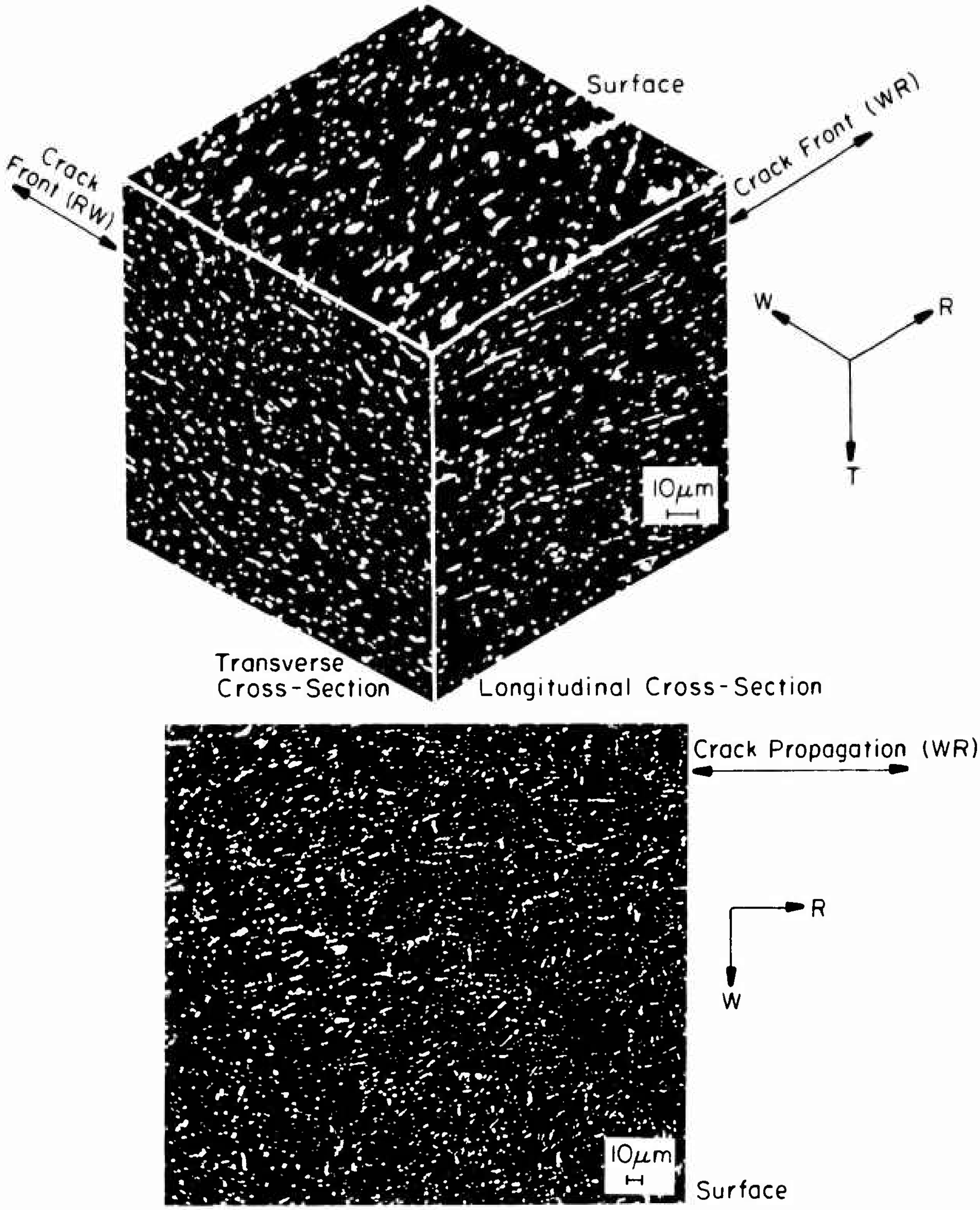
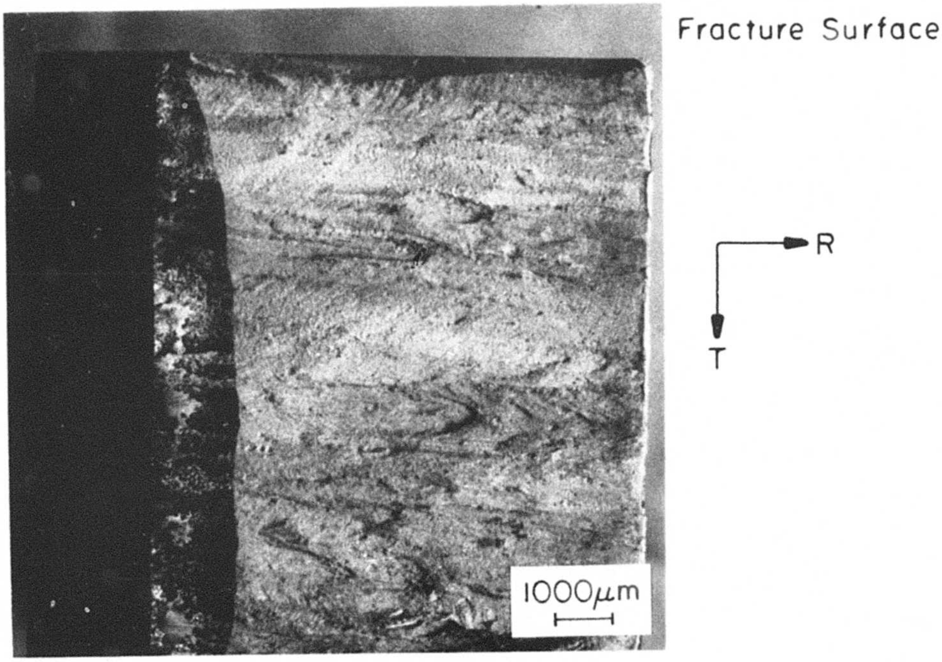


Figure 208 . Alloy 227(7Mo-4Cr-2.5AL). Half inch plate, sample 7WRL2 (Table LXXVIII). Solution annealed 1450F-8 hr WQ, aged 1025F-8 hr. Isometric X500, surface face X250.

YS(ksi):	164 (L)	RA(%):	47 (L)	K_Q(ksi$\sqrt{in}$):	48 (RW)
	178 (T)		32 (T)		43 (WR)



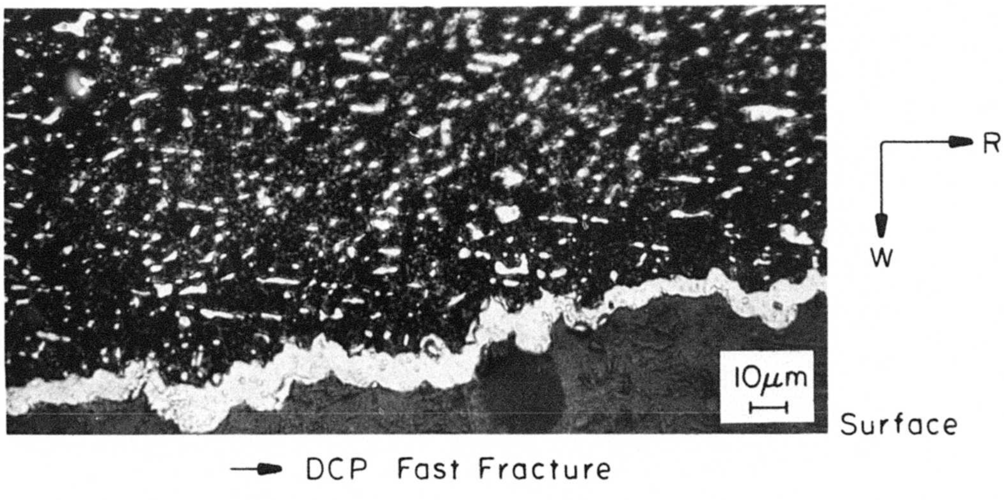


Figure 209. Alloy 227, sample 7WRL2. Fracture surface X8, crack path X500.

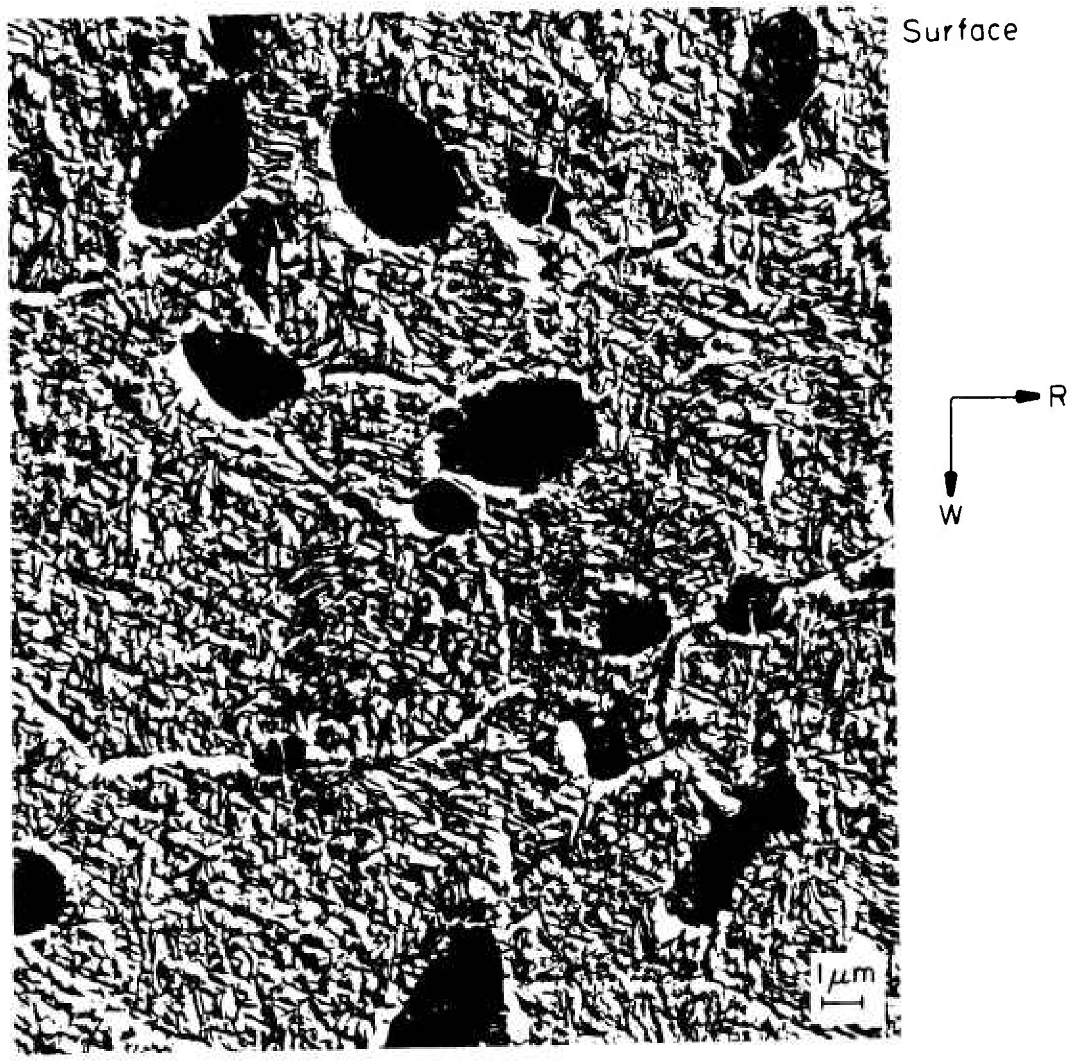
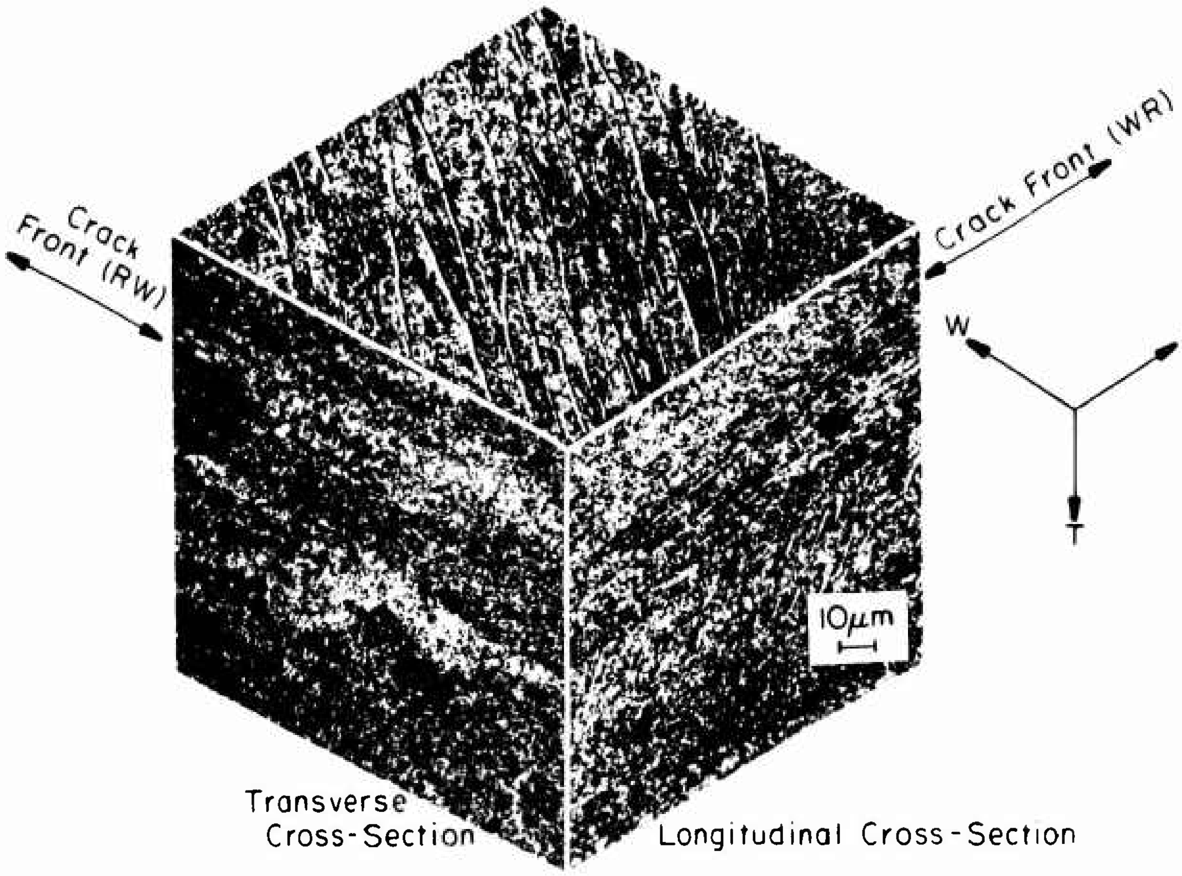


Figure 210. Alloy 227, sample 7WRL2. Surface replica X5200.



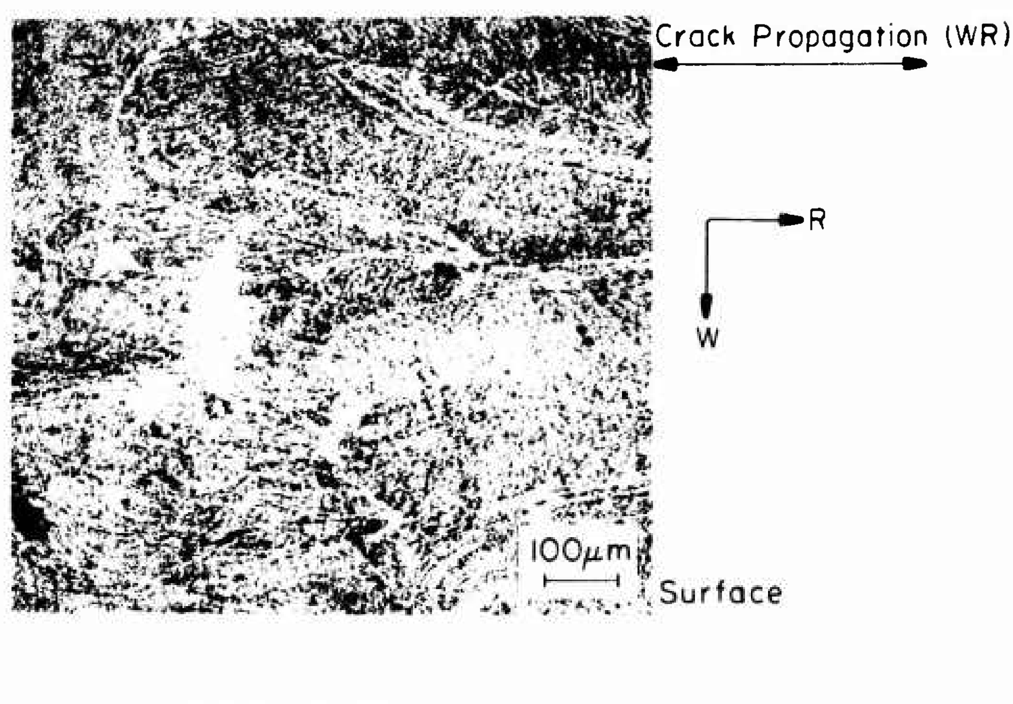
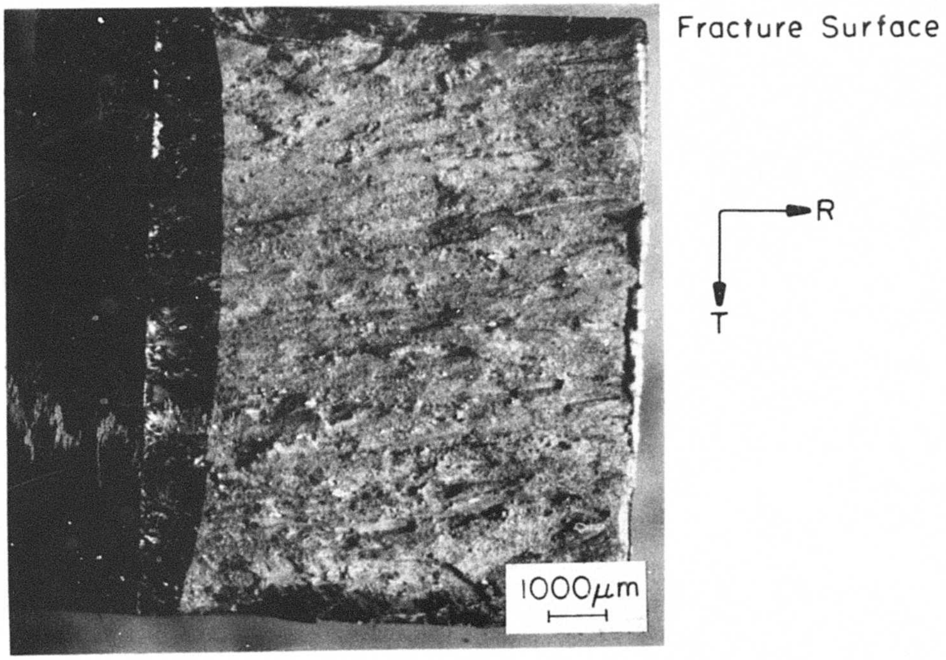


Figure 211. Alloy 253(10Mo-8V-2.5Al). Half inch plate, sample 3WRL2 (Table LXXIX). Solution annealed 1350F-8 hr WQ, aged 950F-96 hr. Isometric X500, surface face X100.

YS(ksi):	170 (L)	RA(%):	6 (L)	K_Q(ksi$\sqrt{\text{in}}$):	49 (RW)
	182 (T)		15 (T)		47 (WR)



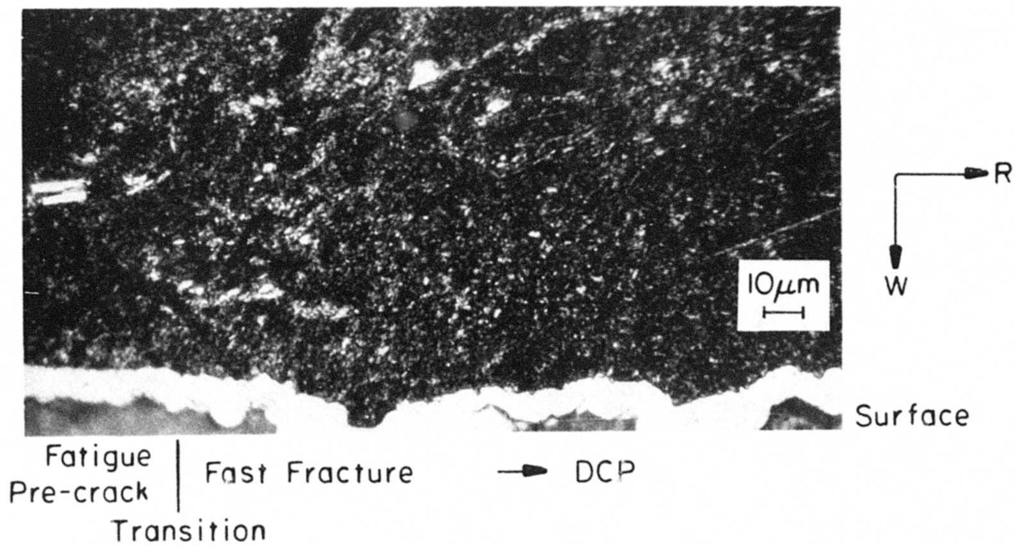


Figure 212. Alloy 253, sample 3WRL2. Fracture surface X8, crack path X500.

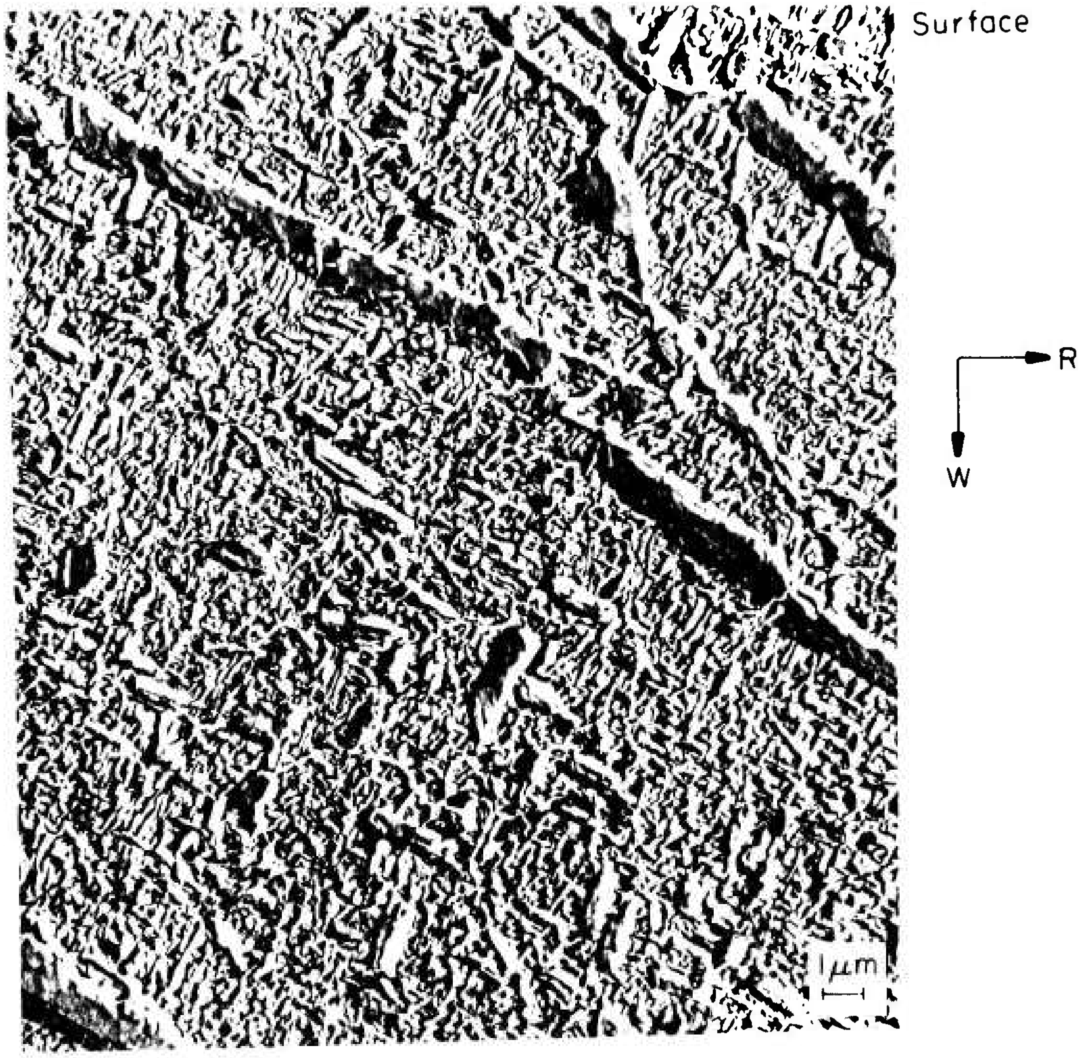
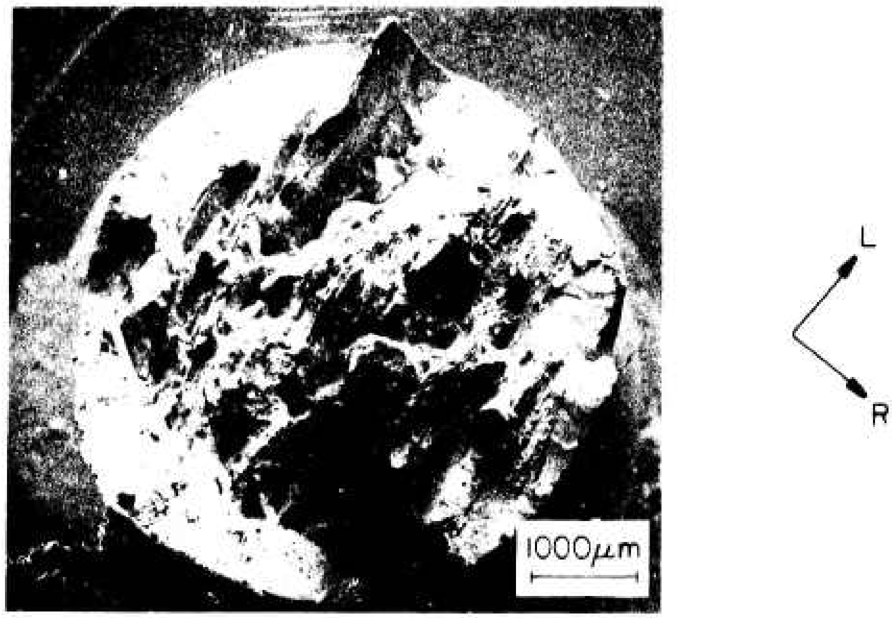


Figure 213. Alloy 253, sample 3WRL2. Surface replica X5200.



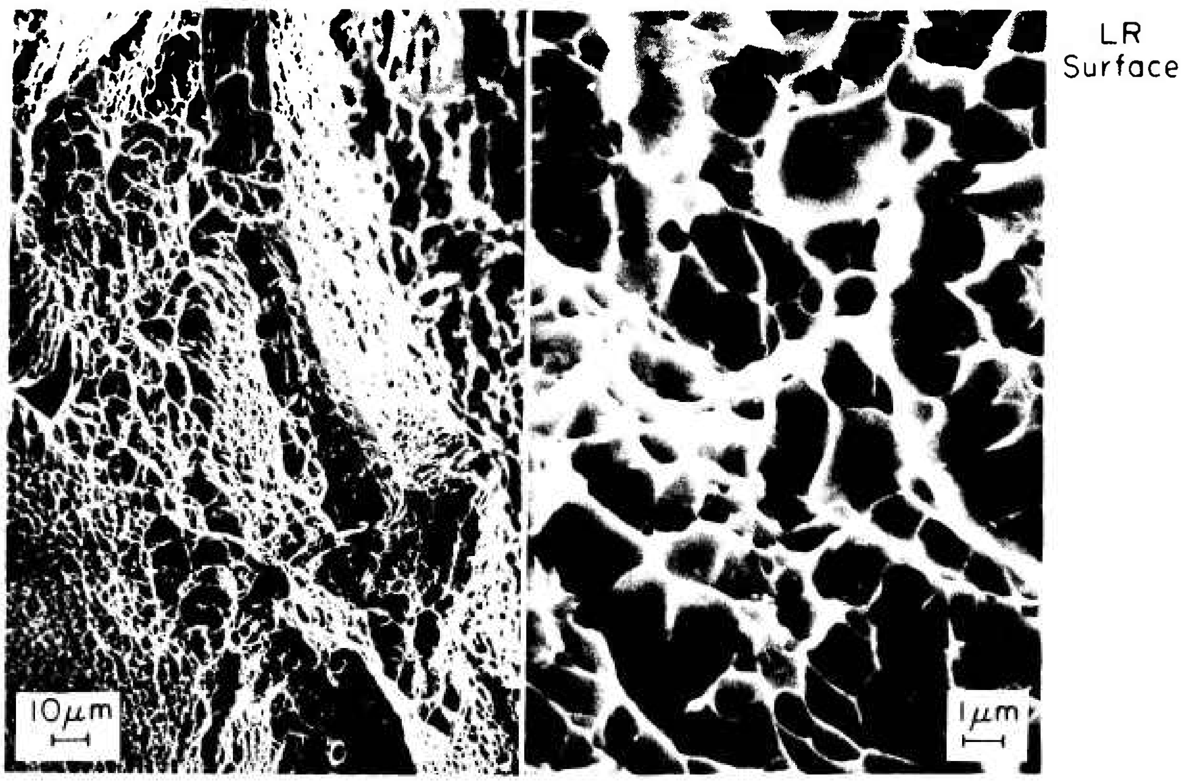


Figure 214. Alloy 334(10Mo-6Cr-2.5Al). Six inch billet full piece center sample 4TC2 (companion sample to 4SLC2, Figure 103, see Table LXVI). Solution annealed 1350F-4 hr WQ plus 1225F-2 hr WQ, aged 900F-96 hr. Fractured sample (top) X15, SEM (left) X375, (right) X5200.

YS(ksi):	147 (L)	RA(%):	50 (L)
	151 (T)		33 (T)

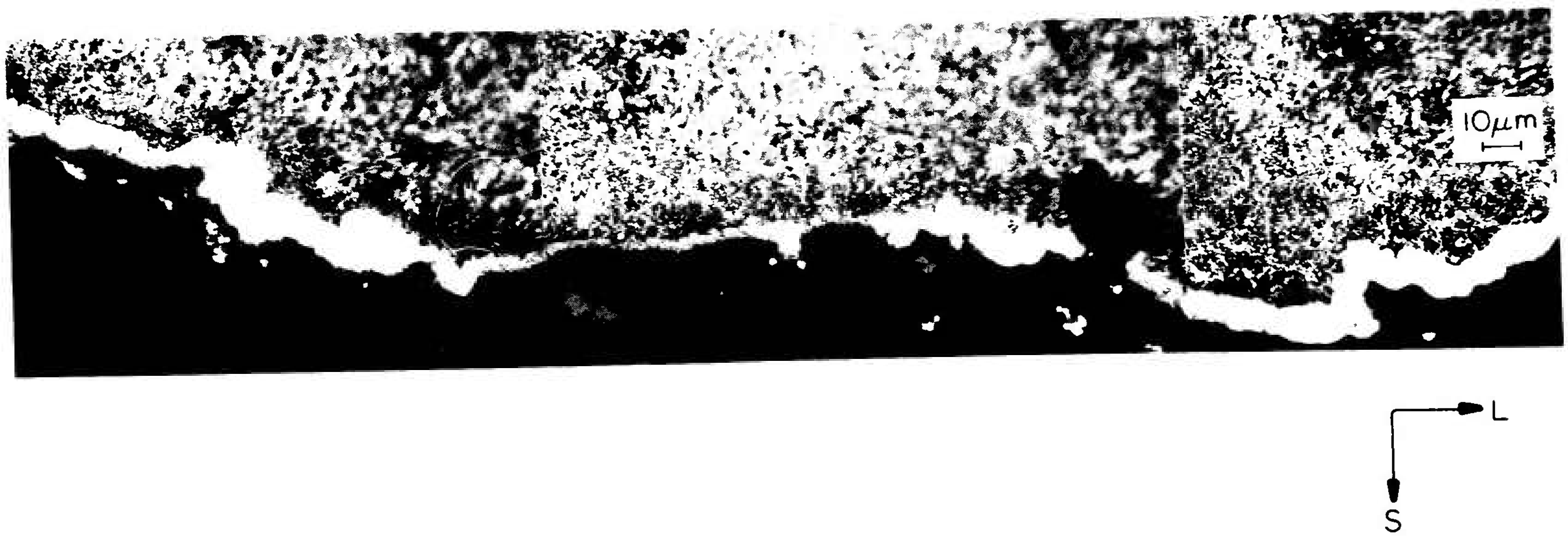


Figure 215. Alloy 334, sample 4TC2. Sectioned tensile sample X500. Note transgranular fracture mode.

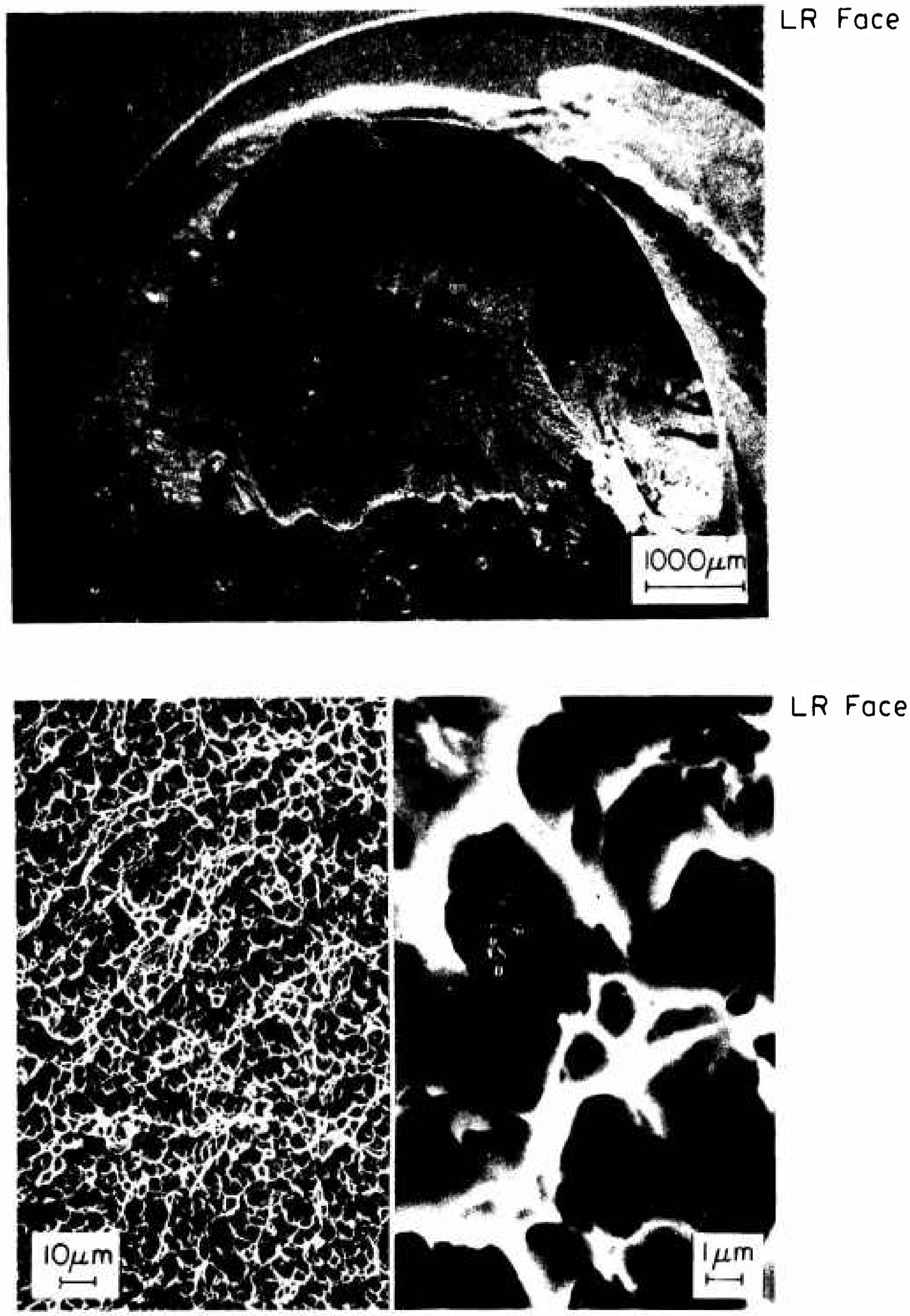


Figure 216. Alloy 227(7Mo-4Cr-2.5Al). Six inch billet slice, sample 7ET3 (companion sample to 7ESR3, Figure 110 Table XLVIII). Solution annealed 1475F-2 hr WQ, aged 1025F-8 hr. Fractured sample (top) X15, SEM X500 (left), X5200 (right).

YS(ksi):	174 (L)	RA(%):	24 (L)
	171 (T)		12 (T)

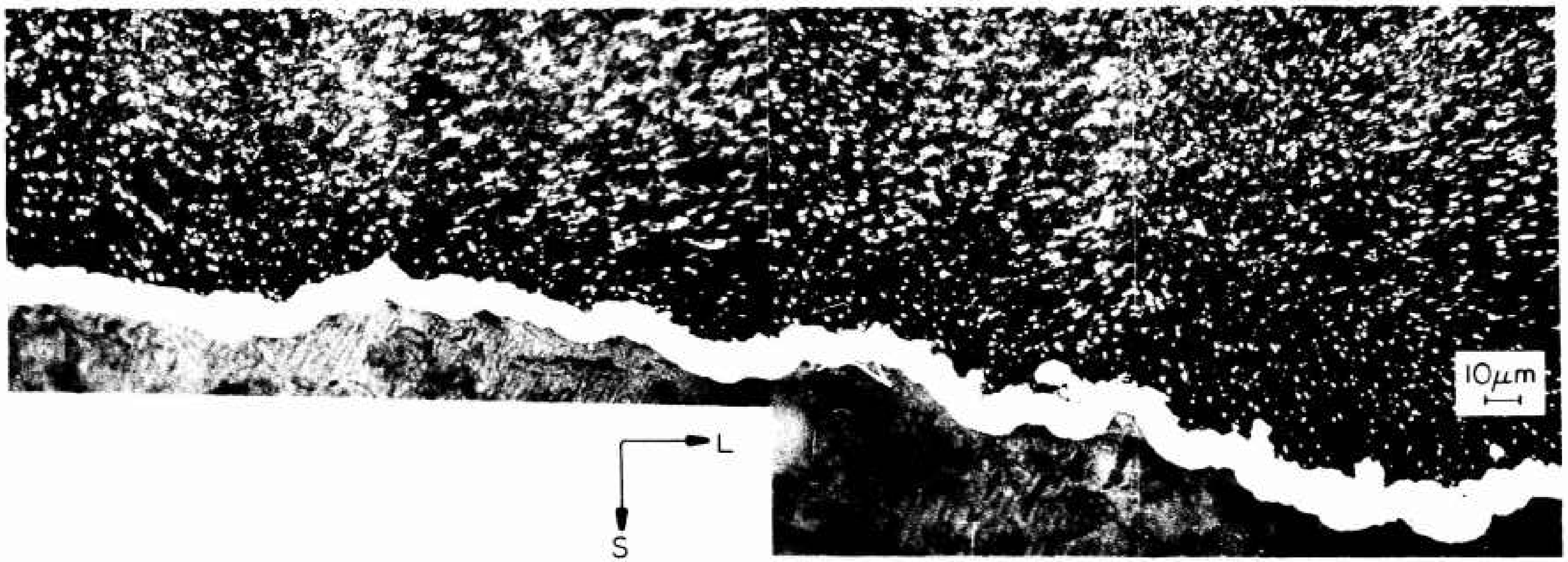


Figure 217. Alloy 227, sample 7ET3. Sectioned tensile sample X500. Note transgranular fracture mode.

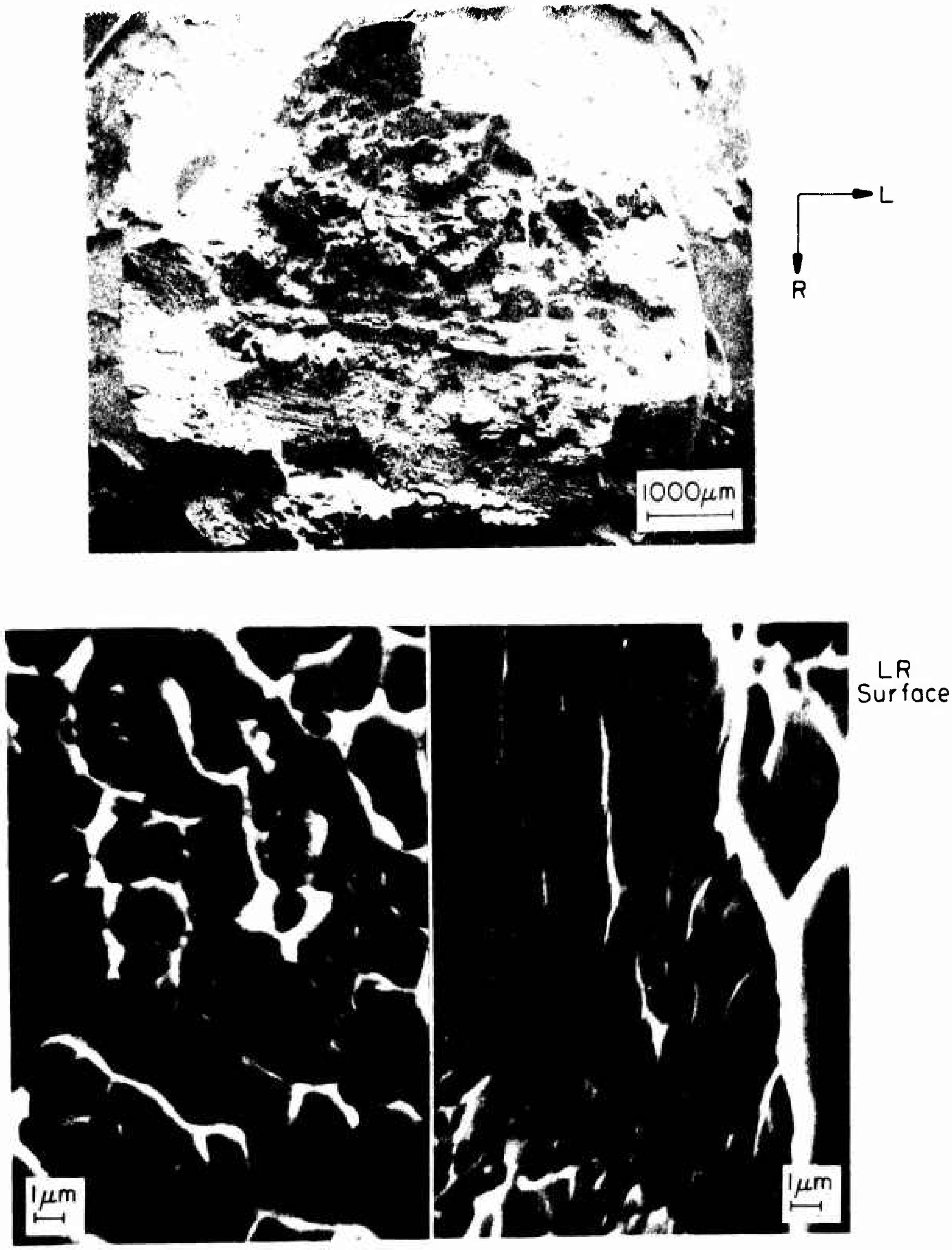


Figure 218. Alloy 227(7Mo-4Cr-2.5Al). Six inch billet slice, sample 7MT7.(Companion sample to 7MSL4, Figure 134 Table LIV). Recrystallize annealed 1575F-0.5 hr WQ, solution annealed 1475F-2 hr, aged 1025F-8 hr. Fractured sample (top) X15, SEM dimpled area (left), smooth area (right) both X5200.

YS(ksi):	180 (L)	RA(%):	5 (L)
	188 (T)		6 (T)

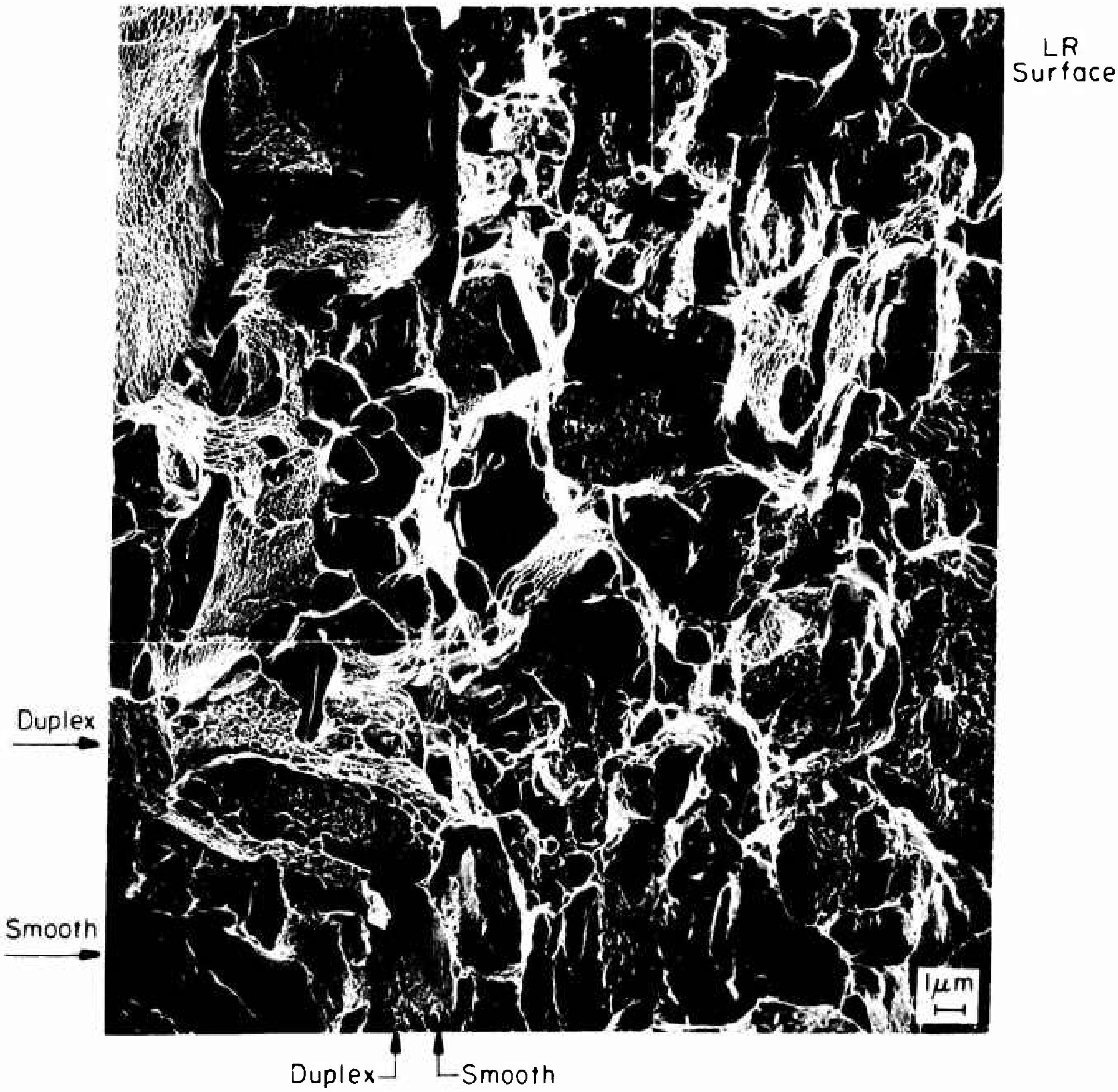


Figure 219. Alloy 227, sample 4MT7. SEM of fracture surface X375. Note indicated dimpled (d) and smooth (S) regions shown at higher magnification in the preceding figure.

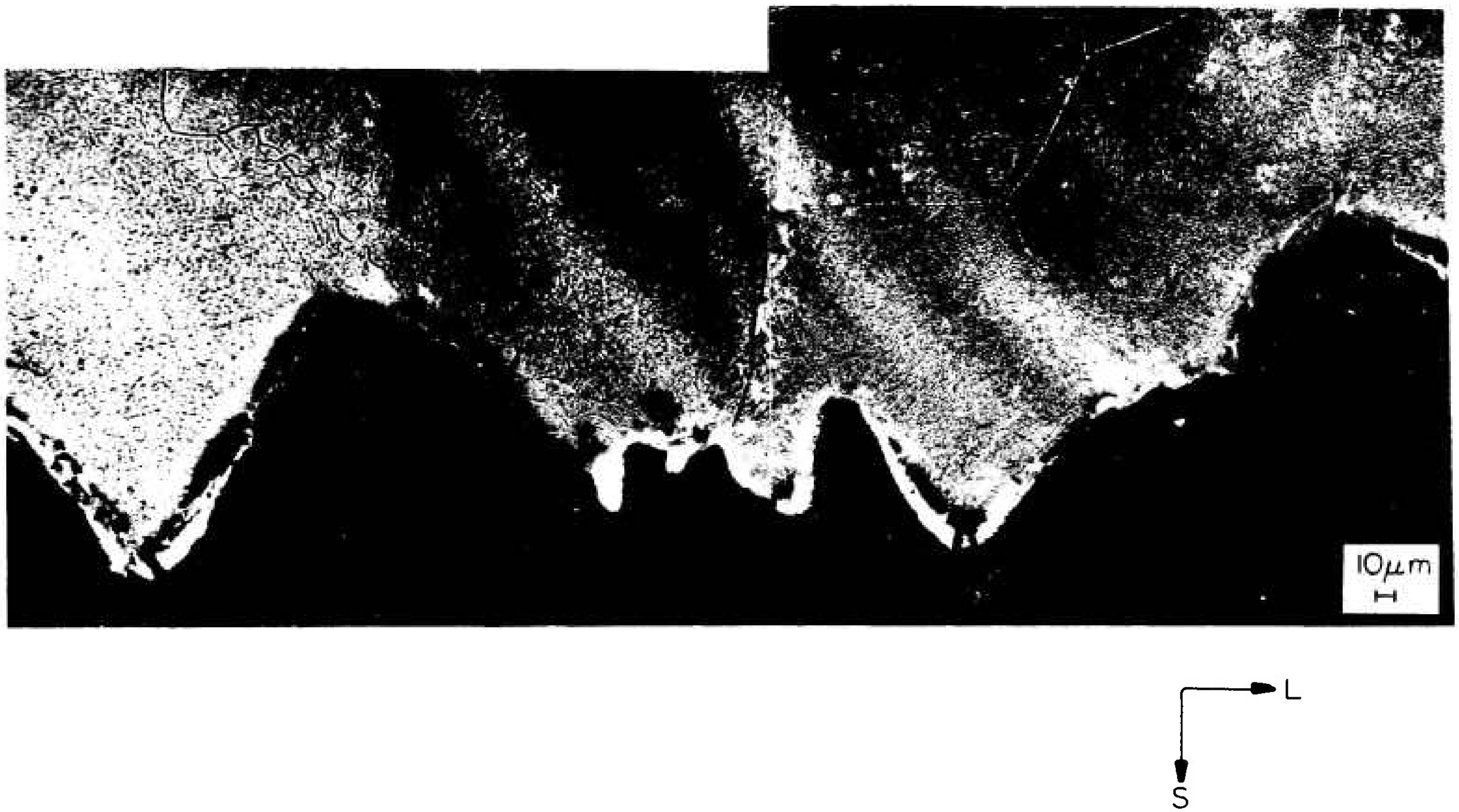


Figure 220. Alloy 227, sample 4MT7. Sectioned tensile sample X250. Note intergranular fracture mode.

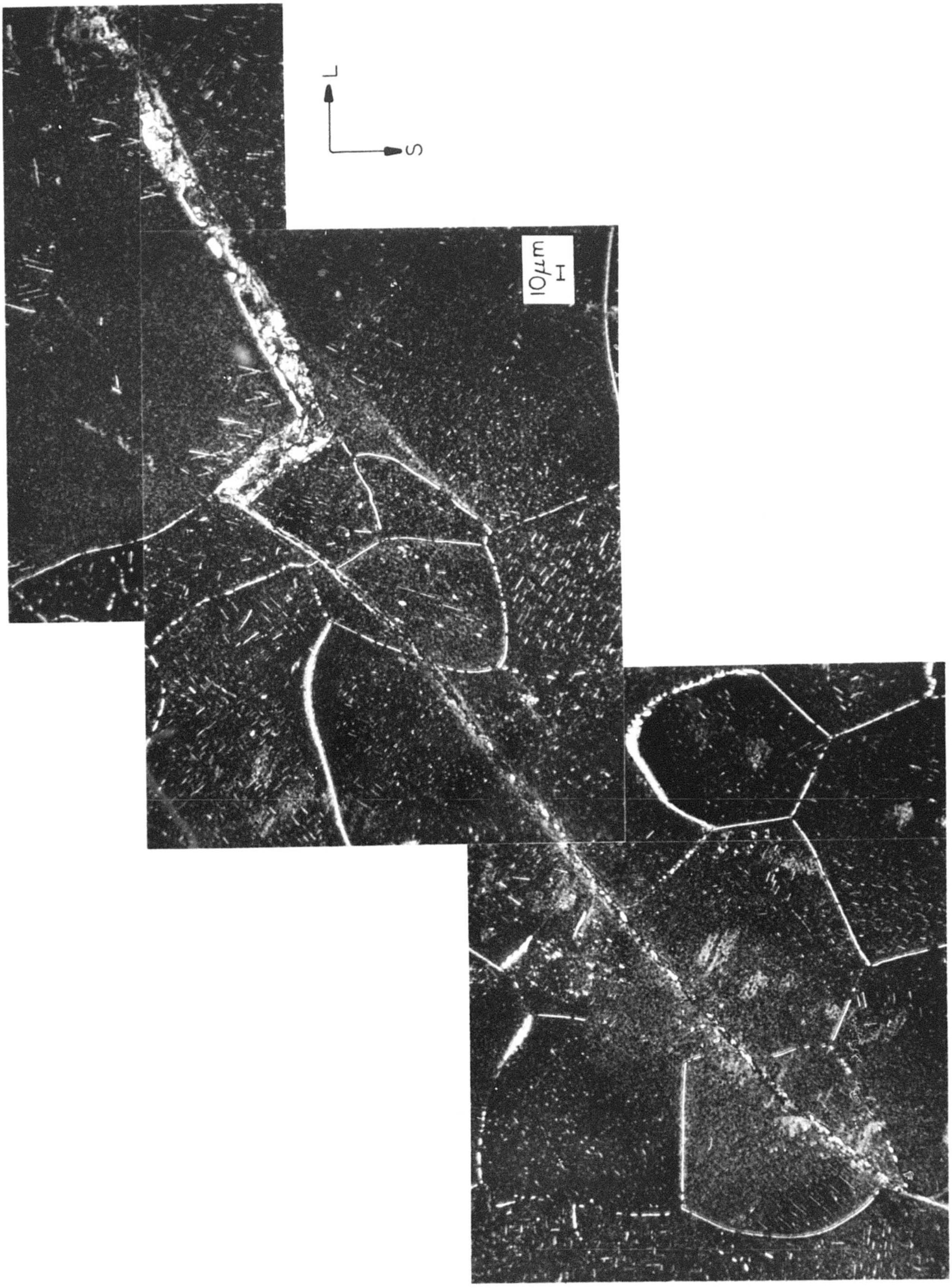


Figure 221. Alloy 227, sample 4MT7. Sectioned tensile sample X250. Side crack exhibiting mixed intergranular/ transgranular fracture mode.

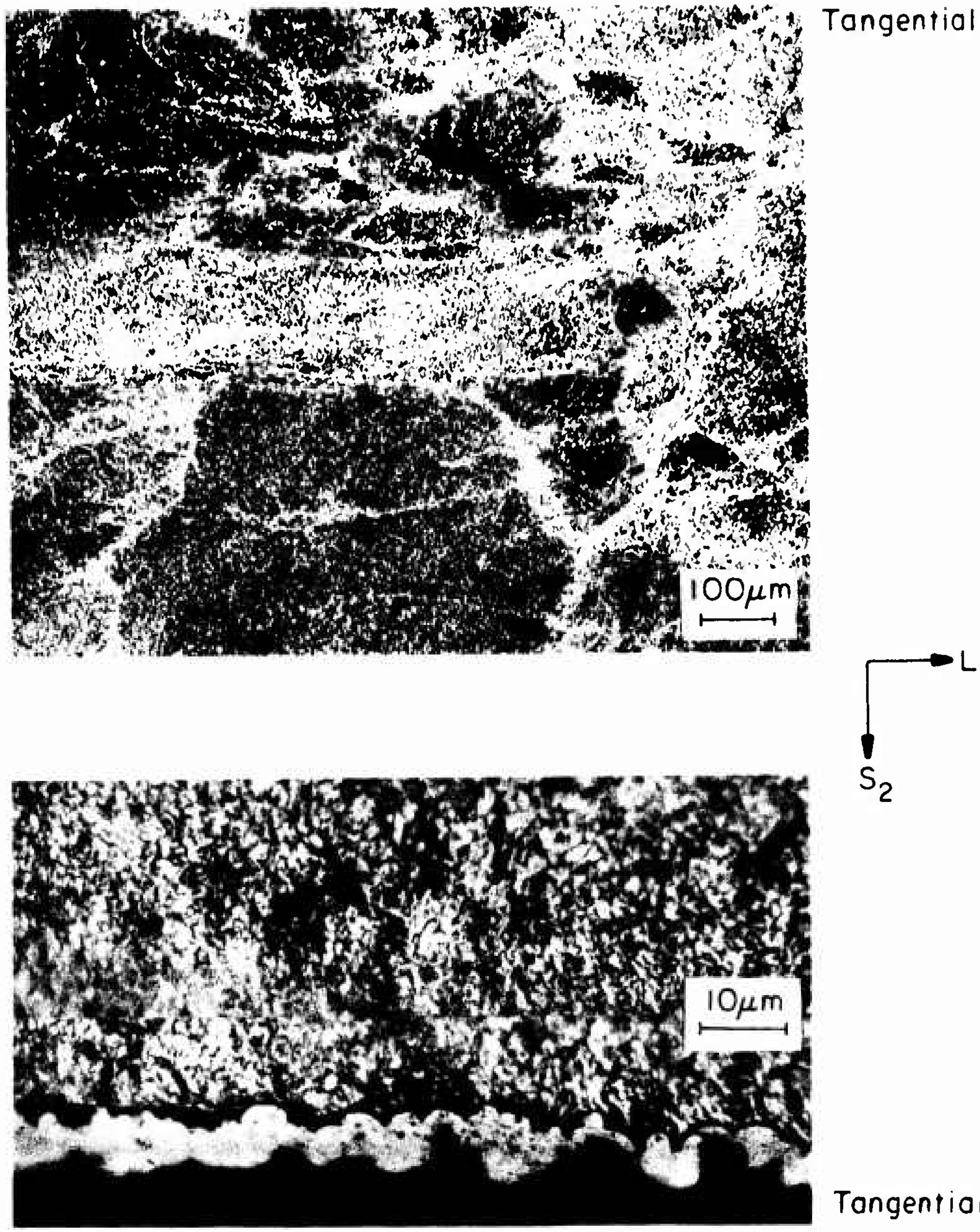


Figure 222. Alloy 334(10Mo-6Cr-2.5Al). Six inch billet full piece, tensile sample 4T4 (Table LXXXI). Duplex solution annealed 1350F-4 hr WQ plus 1225F-2 hr WQ. (Top) X100, (bottom) X1200.

YS(ksi):	129 (L)		RA(%):	52 (L)
	131 (T)			44 (T)

Figure 223. Alloy 334, sample 4T4. Crack path X500.

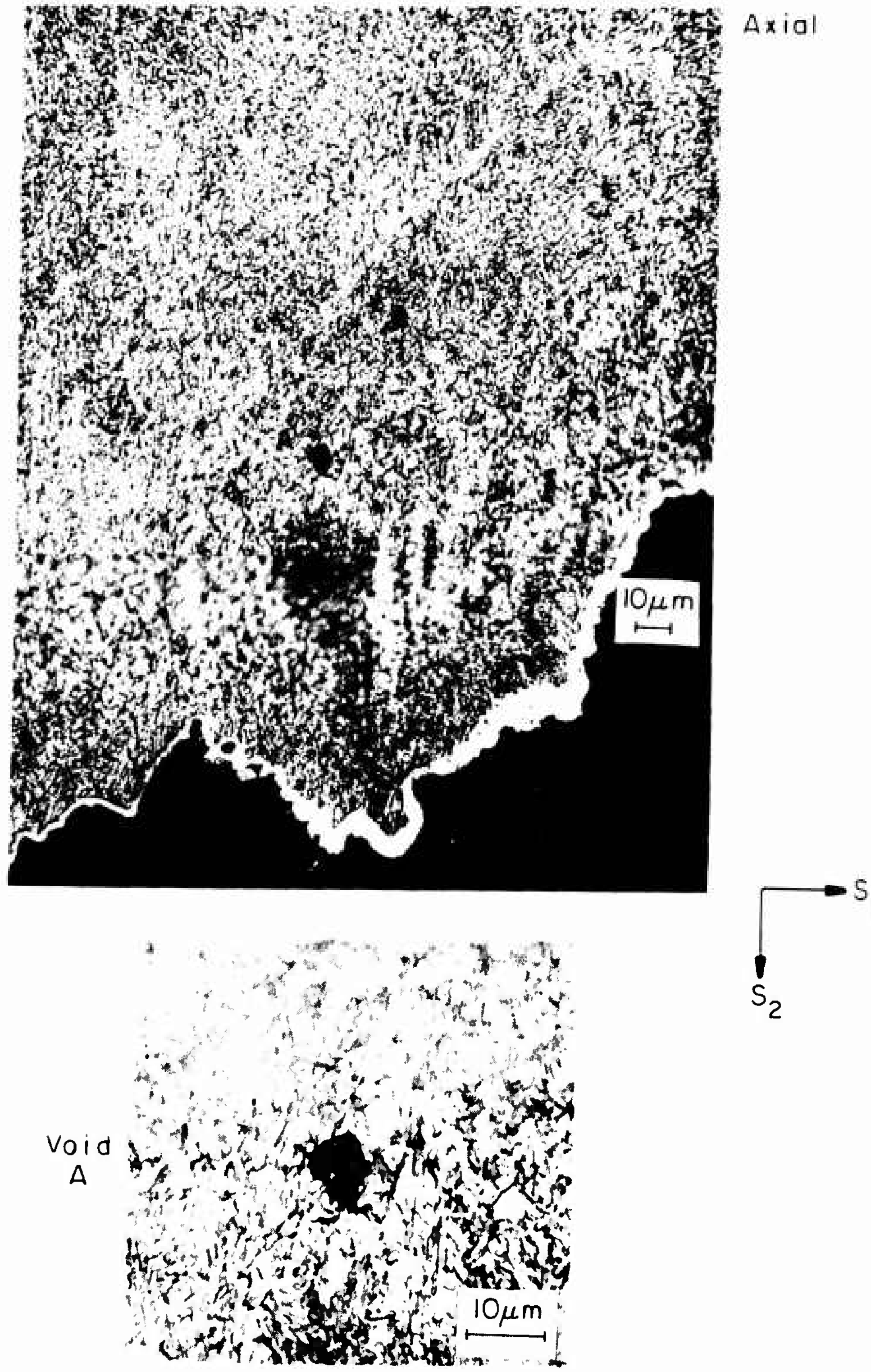


Figure 224. Alloy 334, sample 4T4. Crack path X500. Higher magnification of void X1200.

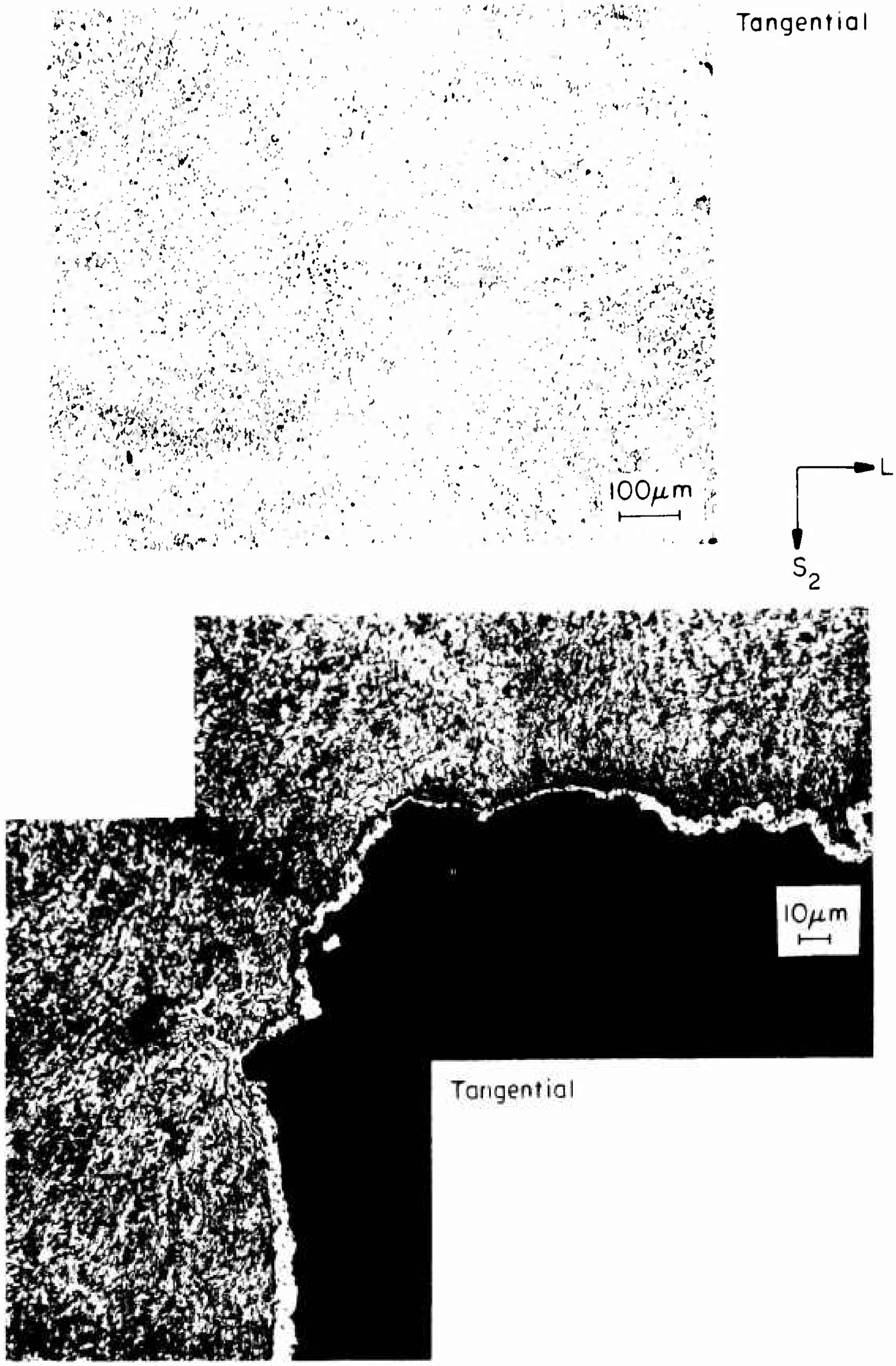


Figure 225. Alloy 227(7Mo-4Cr-2.5Al). Six inch billet full piece, tensile sample 7T2 (Table LXXXI). Duplex solution annealed 1450F-2 hr WQ plus 1350F-8 hr WQ. Tangential face X100, crack path X500.

YS(ksi):	122	(L)	RA(%): 58	(L)
	124	(T)	49	(T)

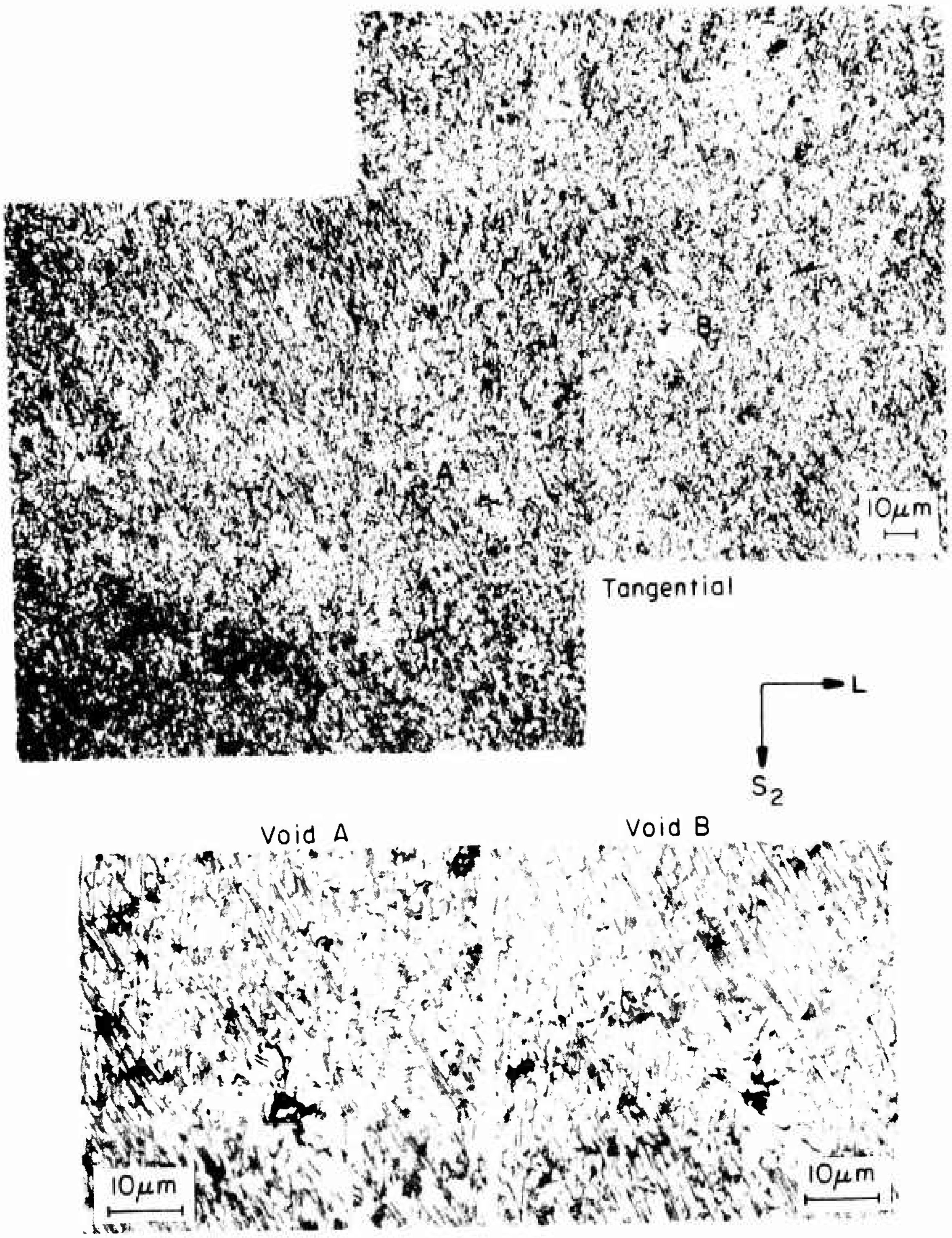


Figure 226. Alloy 227, sample 7T2. Tangential surface just away from fractured surface, note voids indicated. General view X500, higher magnification of voids X1200.

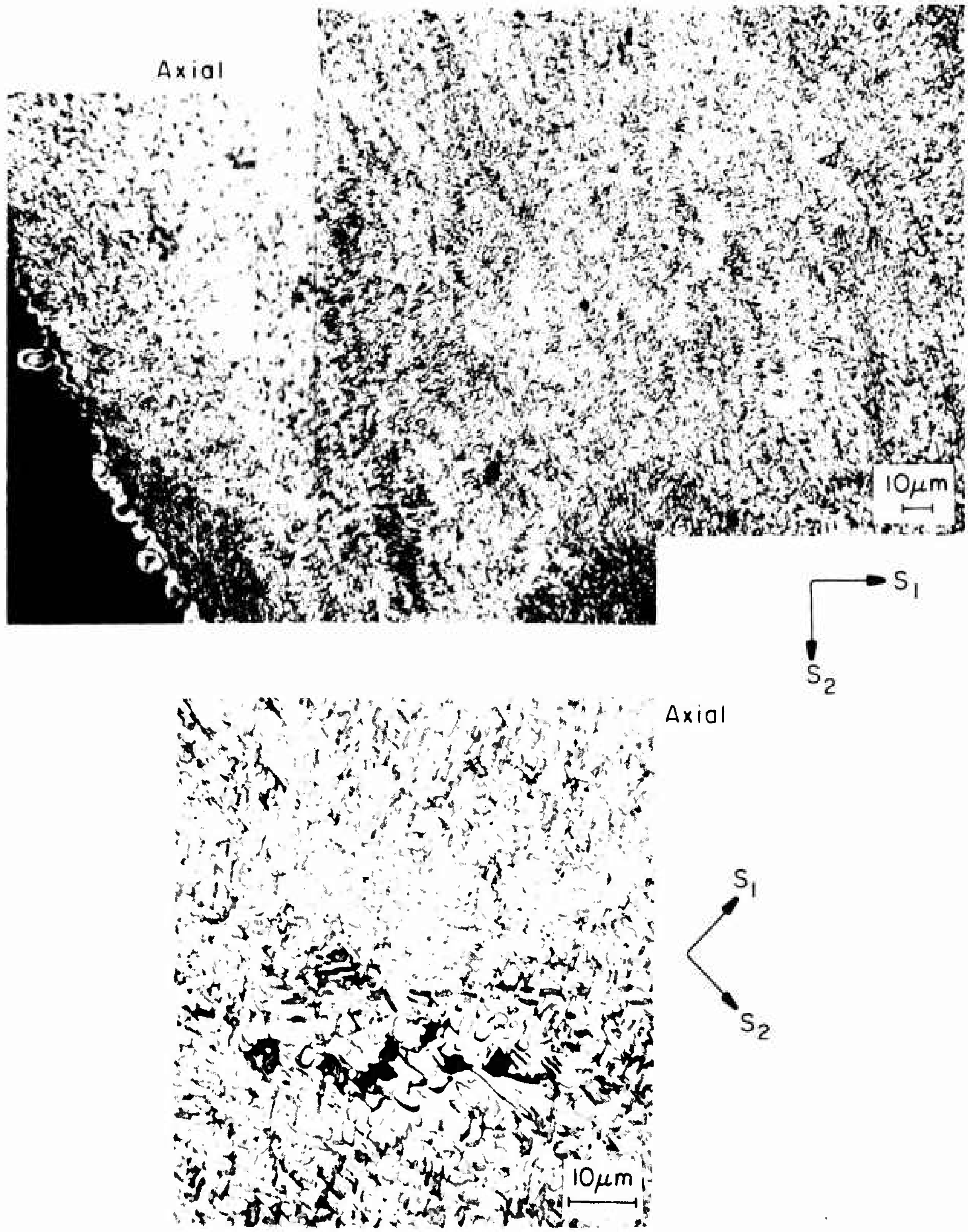


Figure 227. Alloy 227, sample 7T2. Crack path X500, void group adjacent to larger alpha particles X1200.

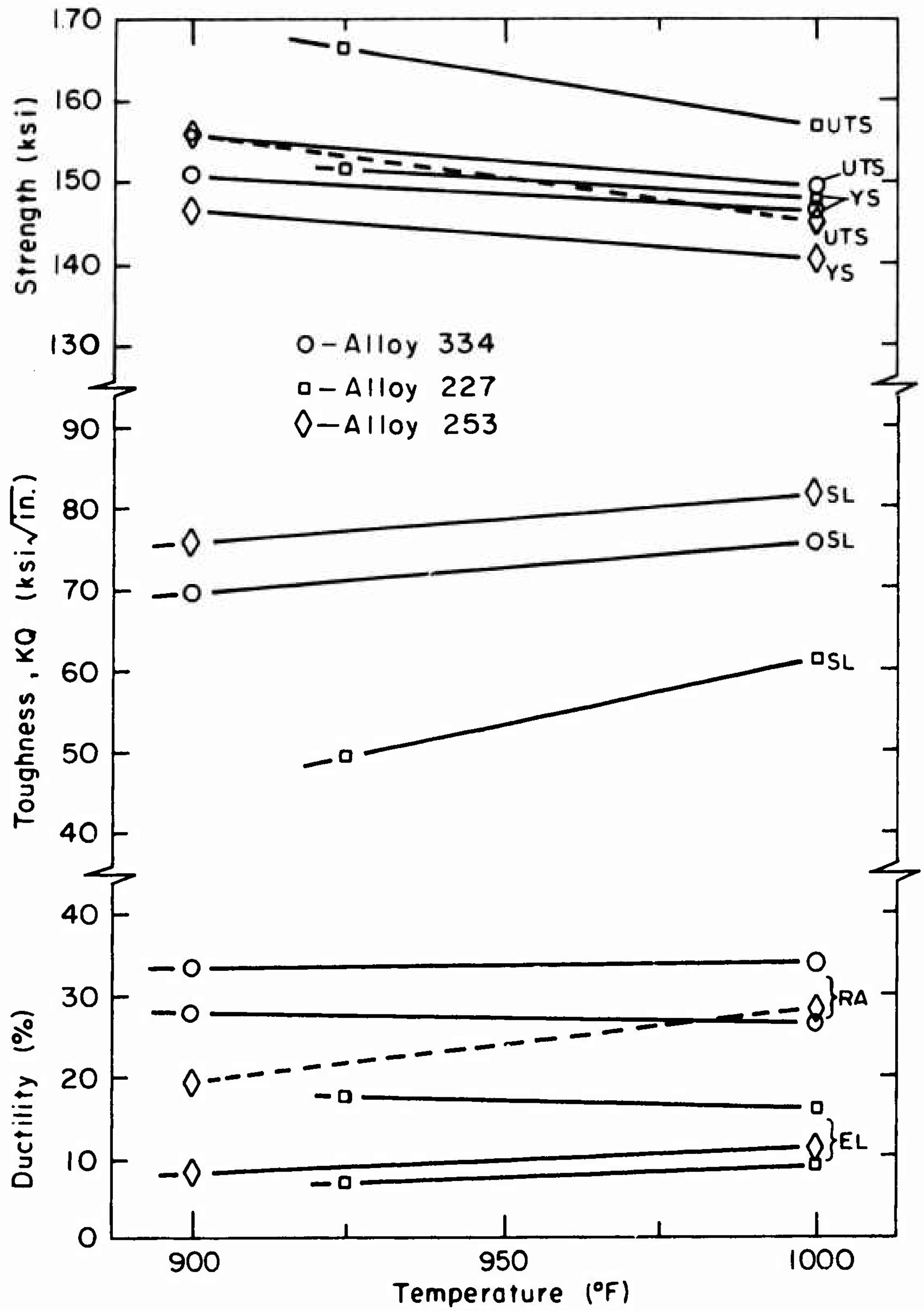


Figure 228. Effect of aging temperture on mechanical properties, transverse center six inch section, for alloy #334 (10Mo-8V-2.5Al), #227 (7Mo-4Cr-2.5Al) and #253 (10Mo-8V-2.5Al).

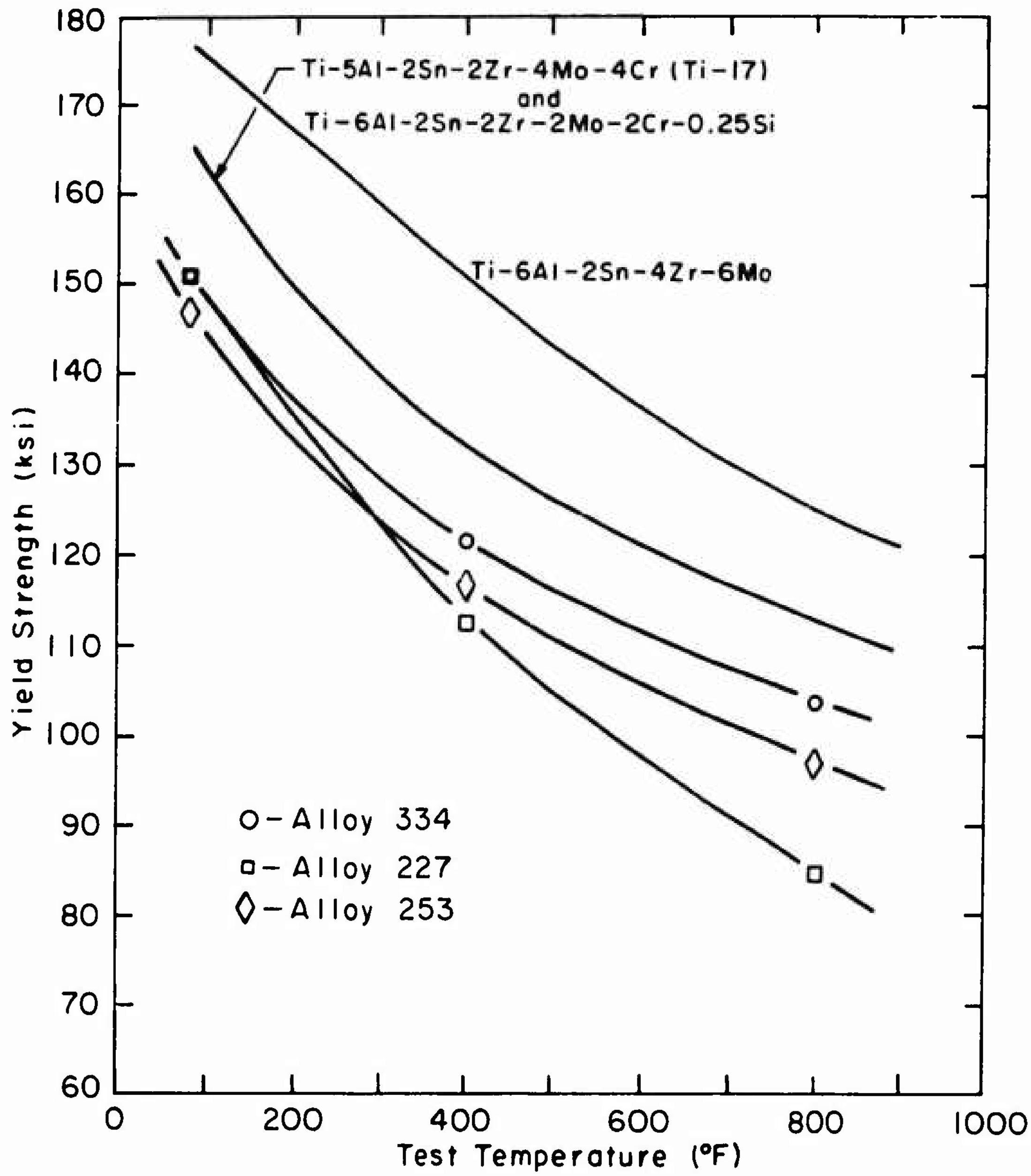


Figure 229. Comparison of elevated temperature transverse yield strength, center six inch section contract alloys with reported data from other deep hardenable alloys[27] (longitudinal direction for 6-22-22S, not specified for other alloys). Note that present alloys, heat-treated to a lower strength condition, follow similar trend lines.

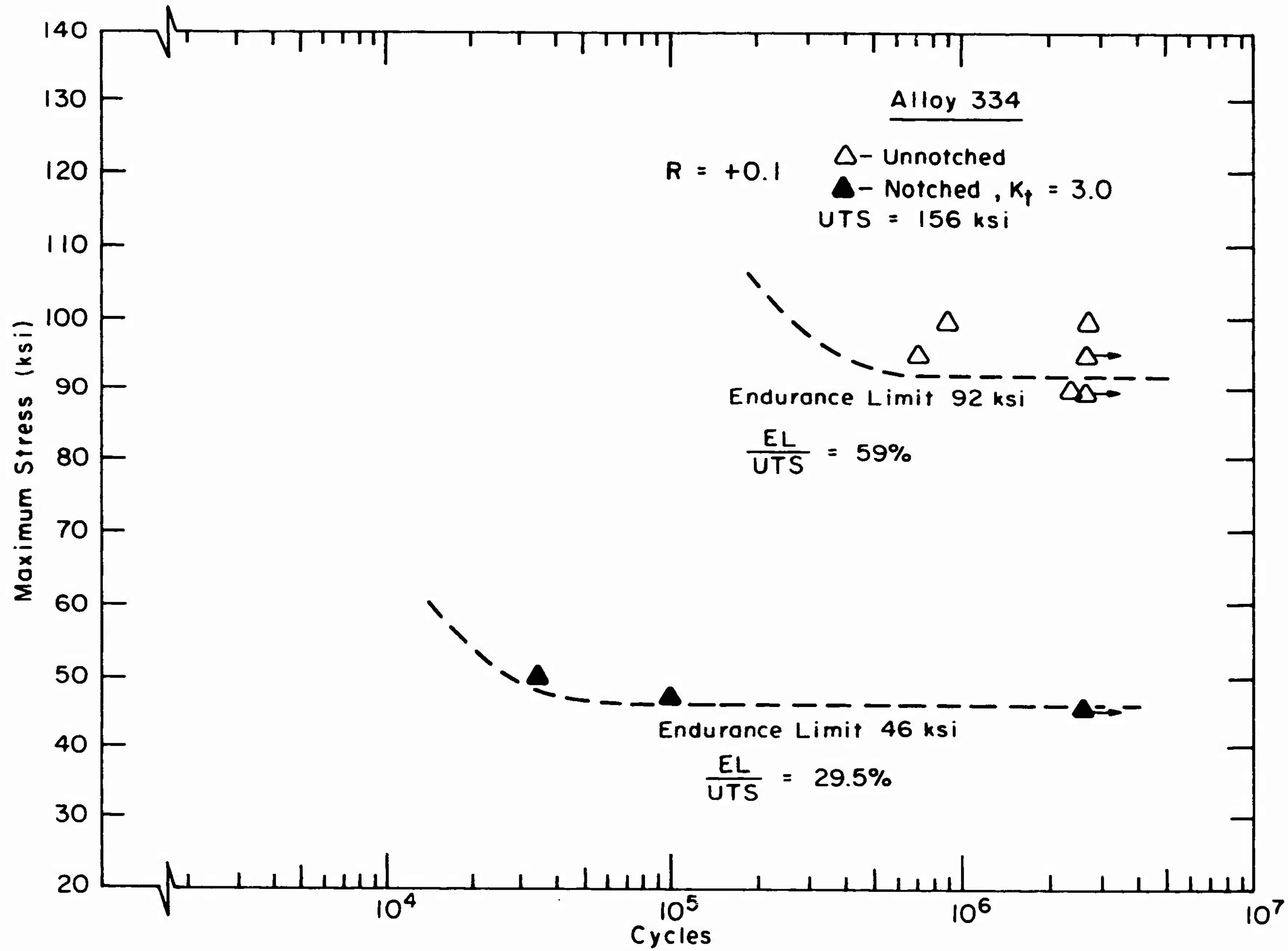


Figure 230. Fatigue behavior of alloy 334 (10Mo-6Cr-2.5Al). Transverse samples, center location 6 inch section.

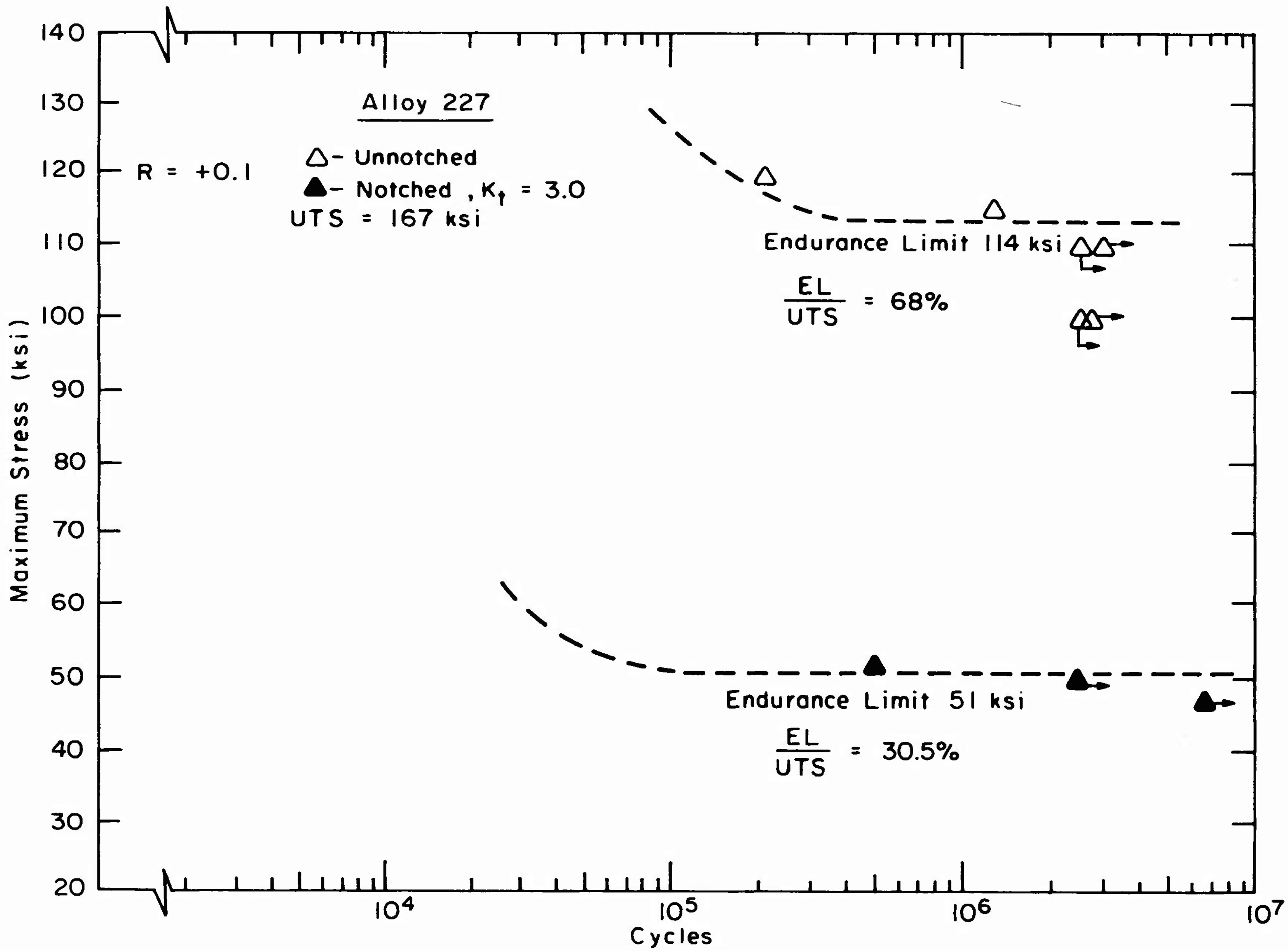


Figure 231. Fatigue behavior of alloy 227 (7Mo-4Cr-2.5Al). Transverse samples, center location 6 inch section

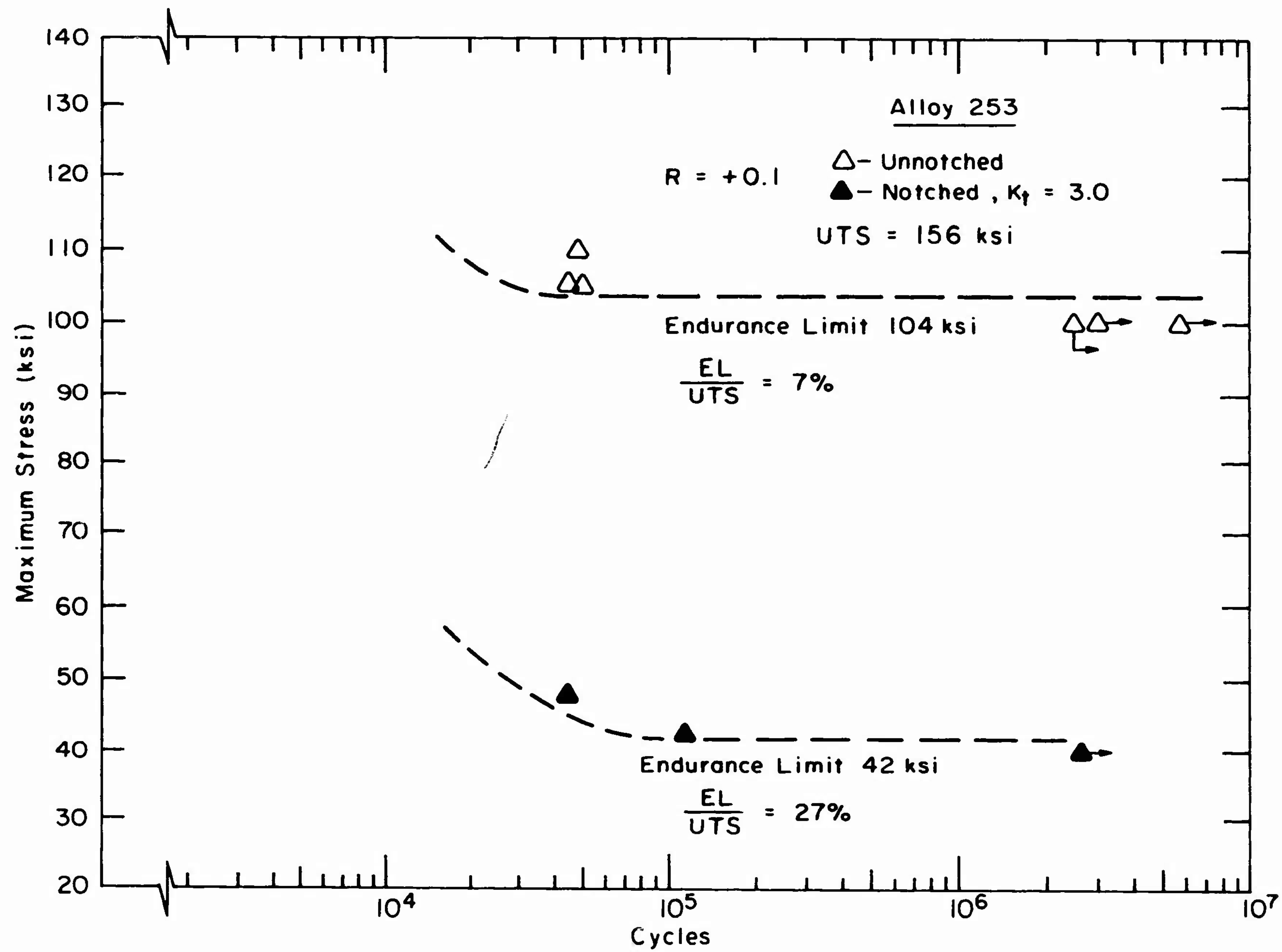


Figure 232. Fatigue behavior of alloy 253 (10Mo-8V-2.5Al). Transverse samples, center location 6 inch section.

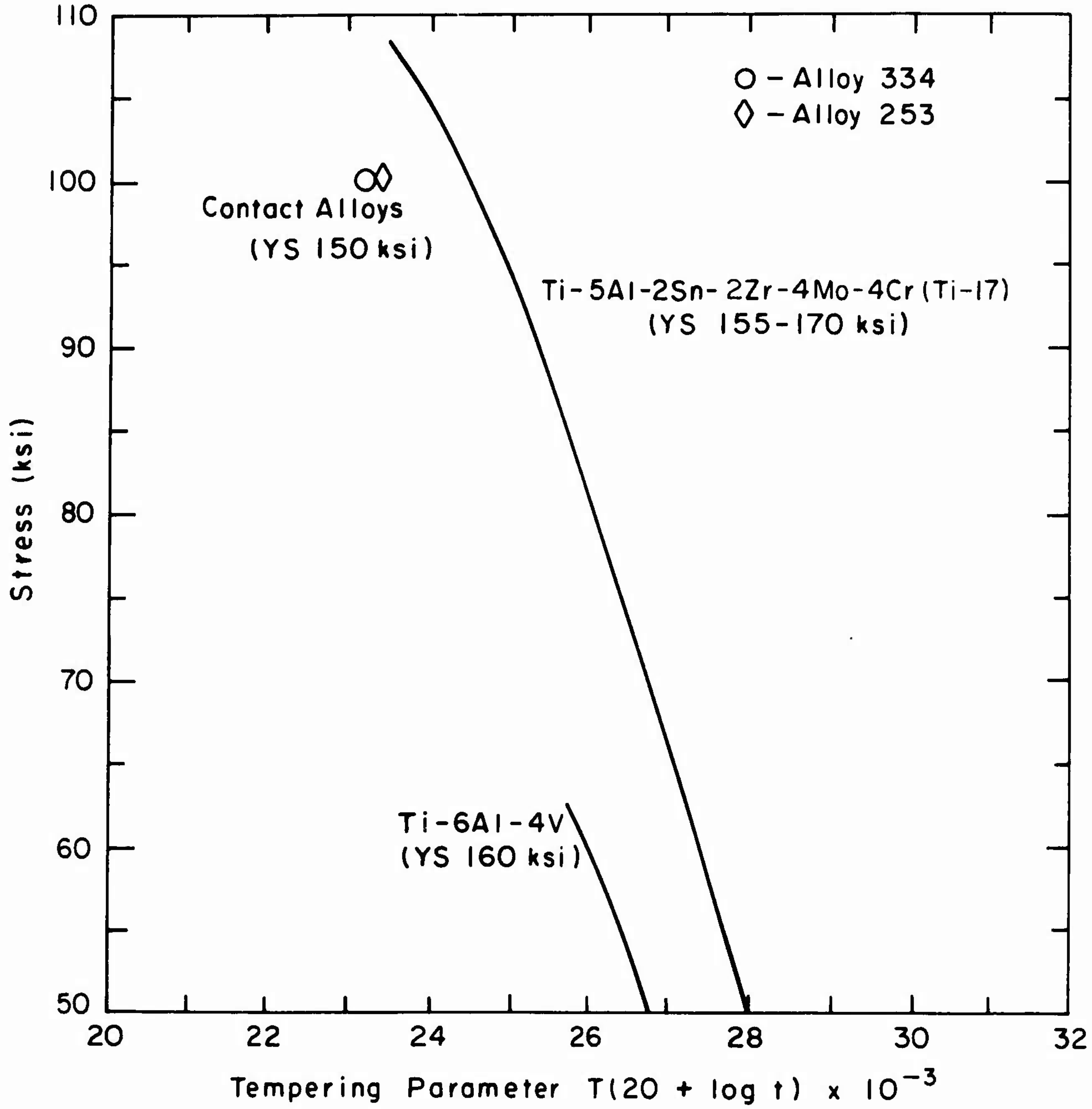


Figure 233. Larson-Miller creep curves at 0.2% plastic deformation for contract alloys and other titanium alloys(28, 42) at the 150-170 ksi yield strength level.

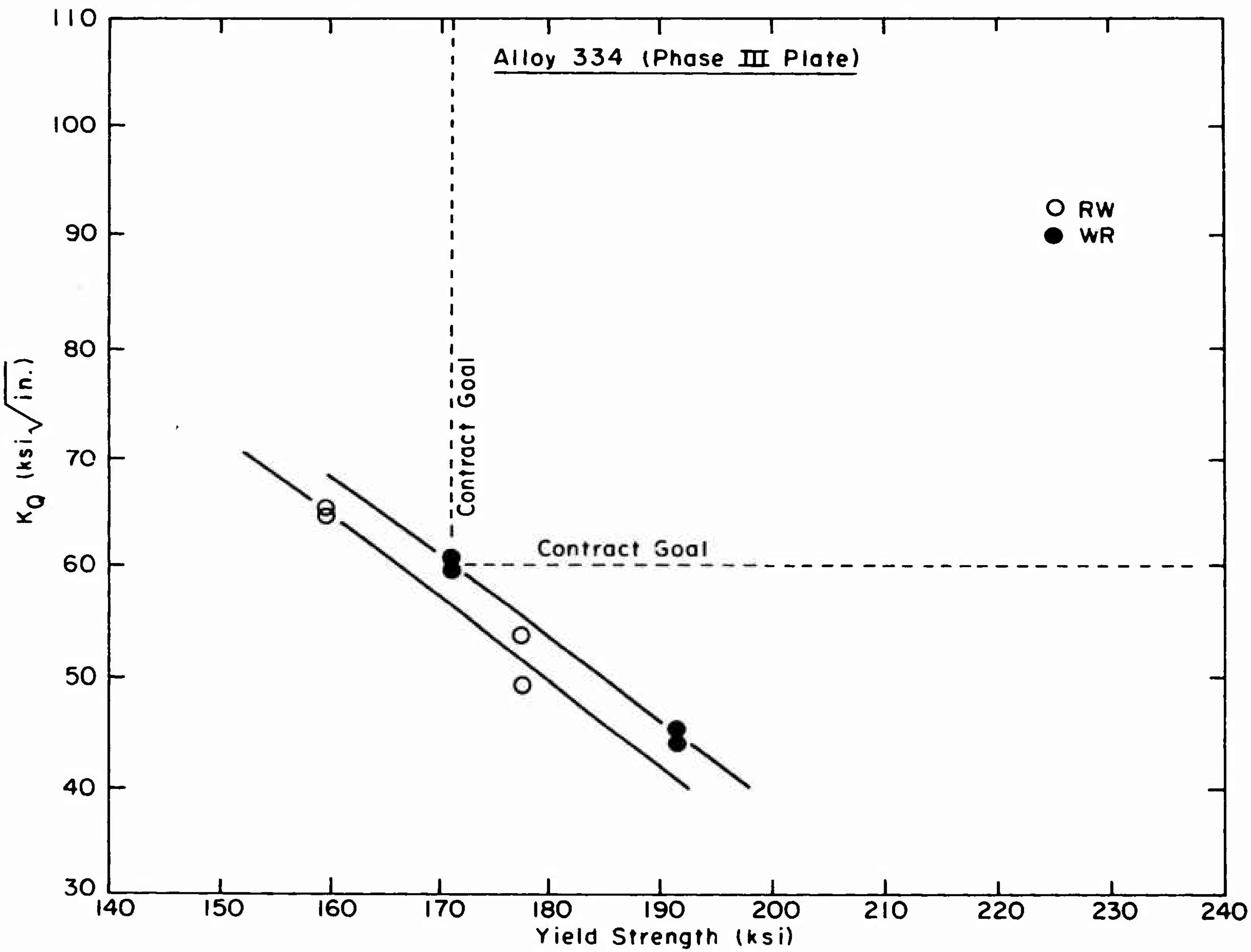


Figure 234. Alloy 334 (10Mo-6Cr-2.5Al), Phase III half-inch plate. Toughness (K_Q) - yield strength trend lines.

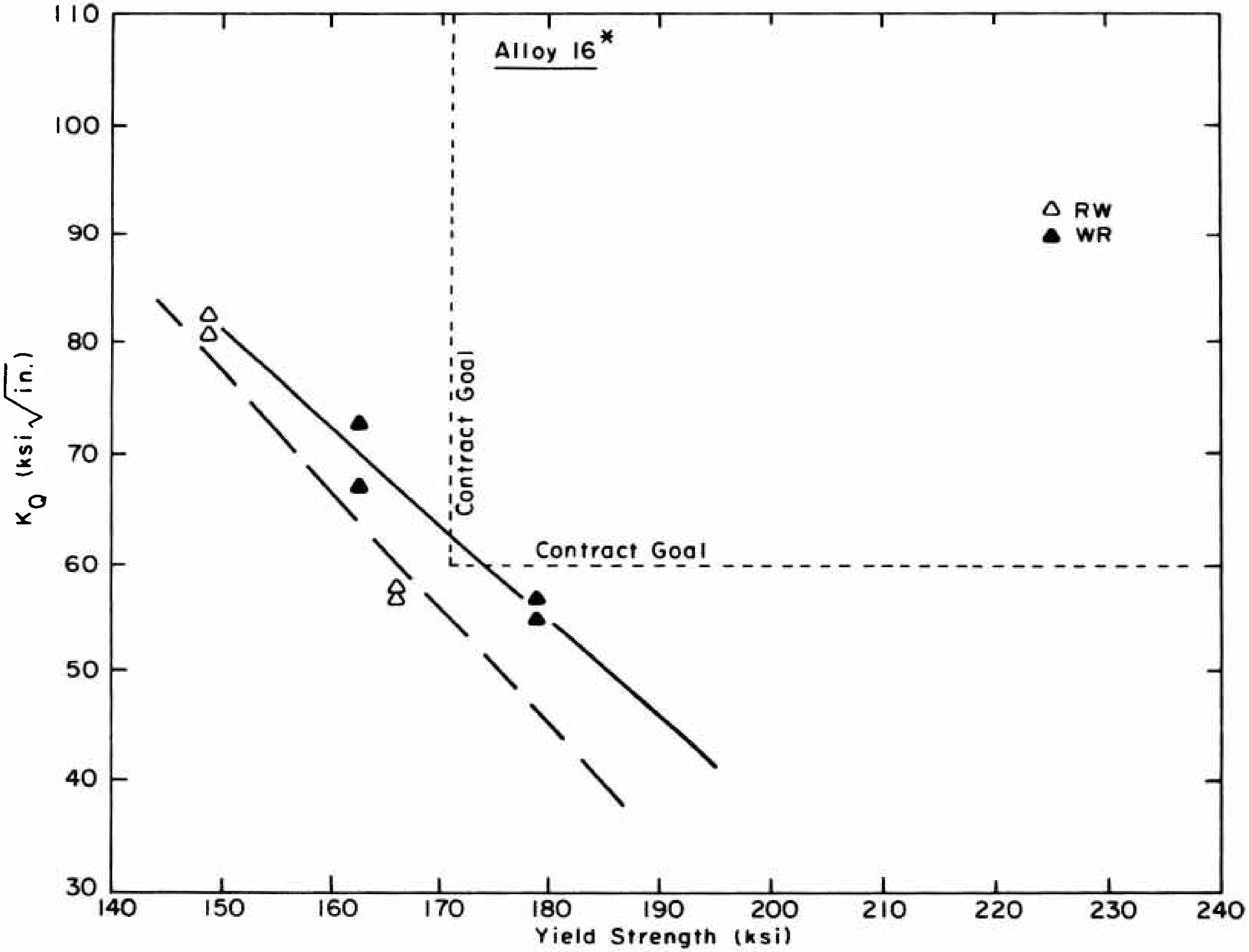


Figure 235. Alloy 16 (8Mo-4.5Cr-2.5Al). Half inch plate. *Data developed under the NAVAIR program.(22) Toughness (K_Q) - Yield strength trend lines.

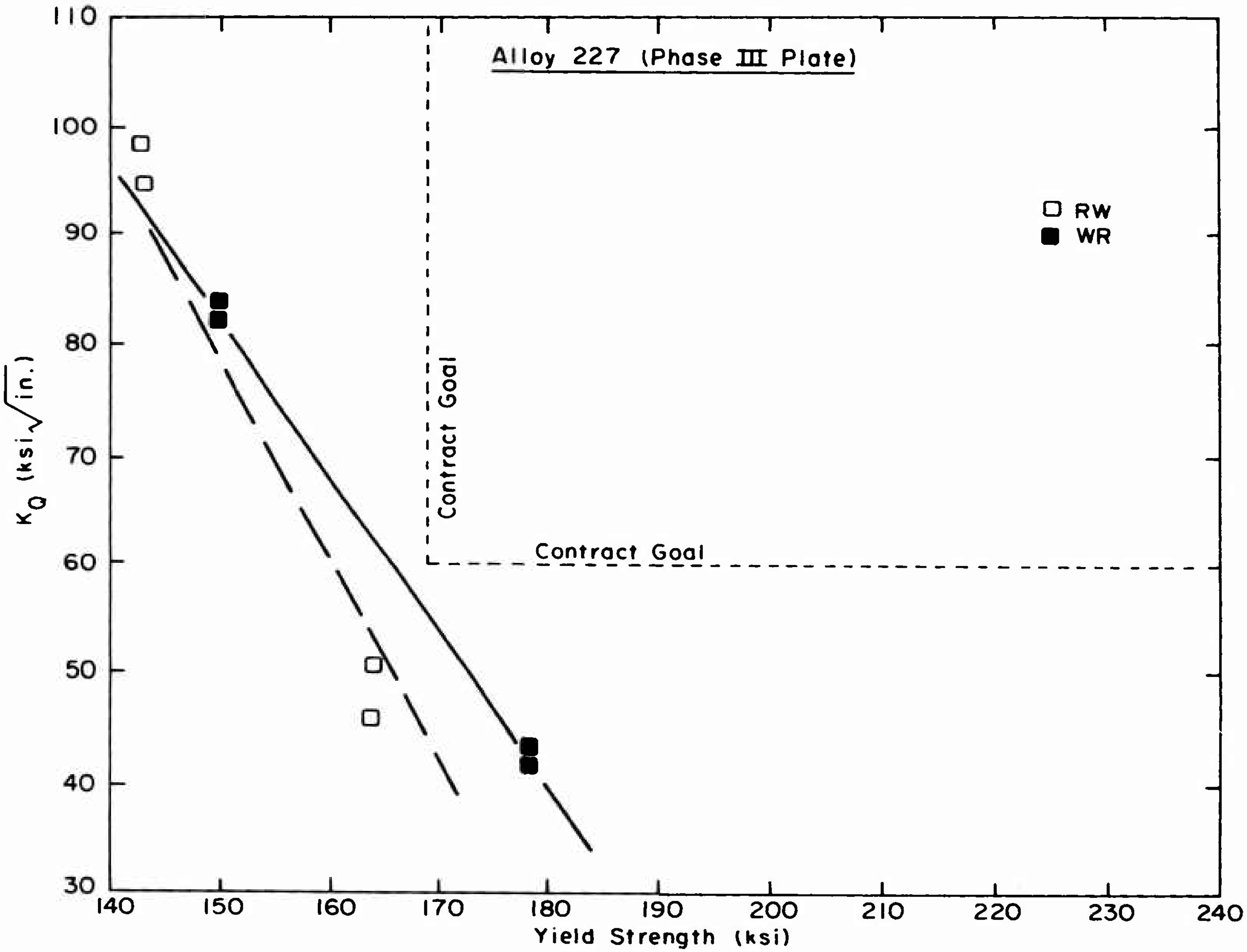


Figure 236. Alloy 227 (7Mo-4Cr-2.5Al), Phase III half-inch plate. Toughness (K_Q) - Yield strength trend lines.

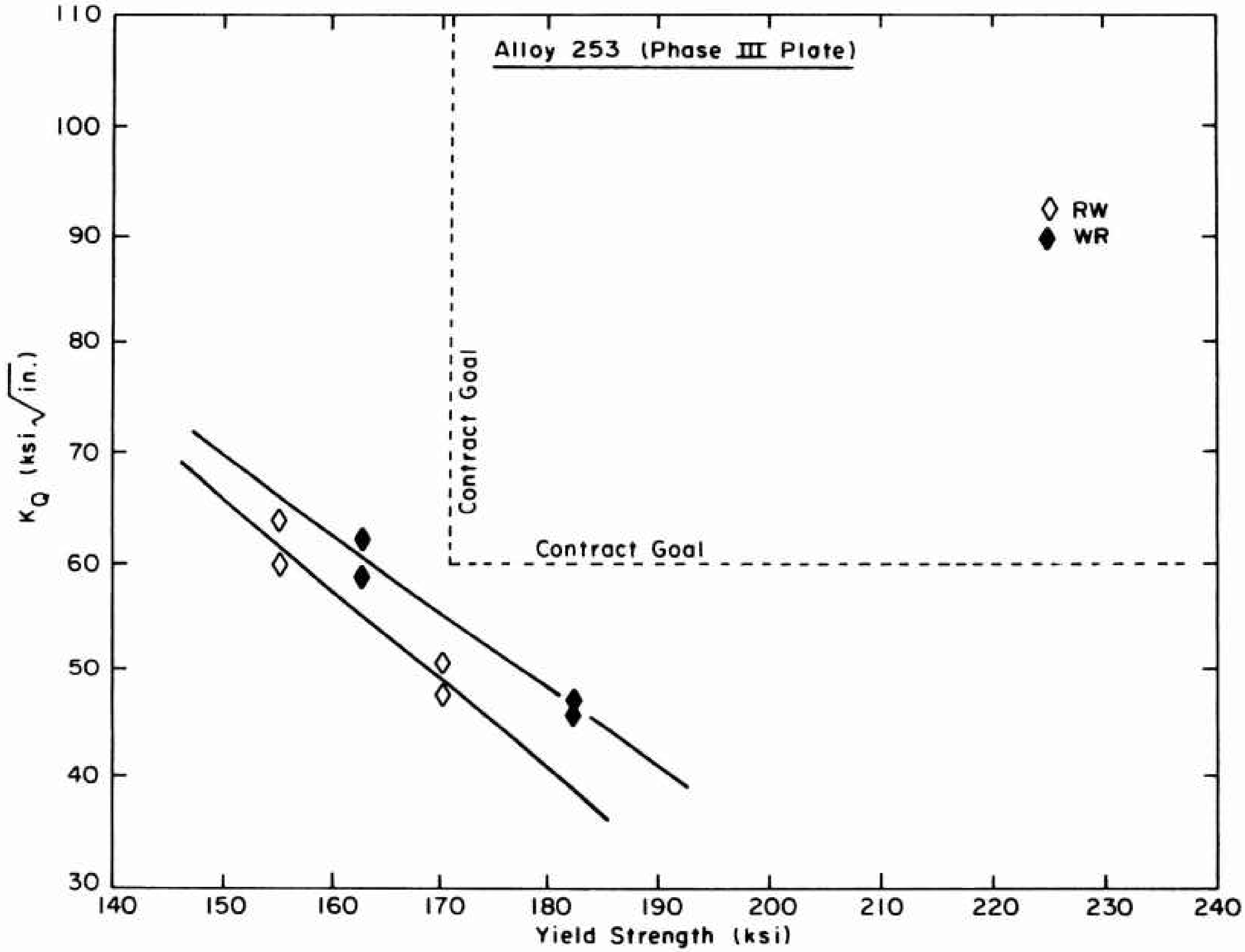


Figure 237. Alloy 253 (10Mo-8V-2.5Al), Phase III half-inch plate. Toughness (K_Q) - Yield strength trend lines.

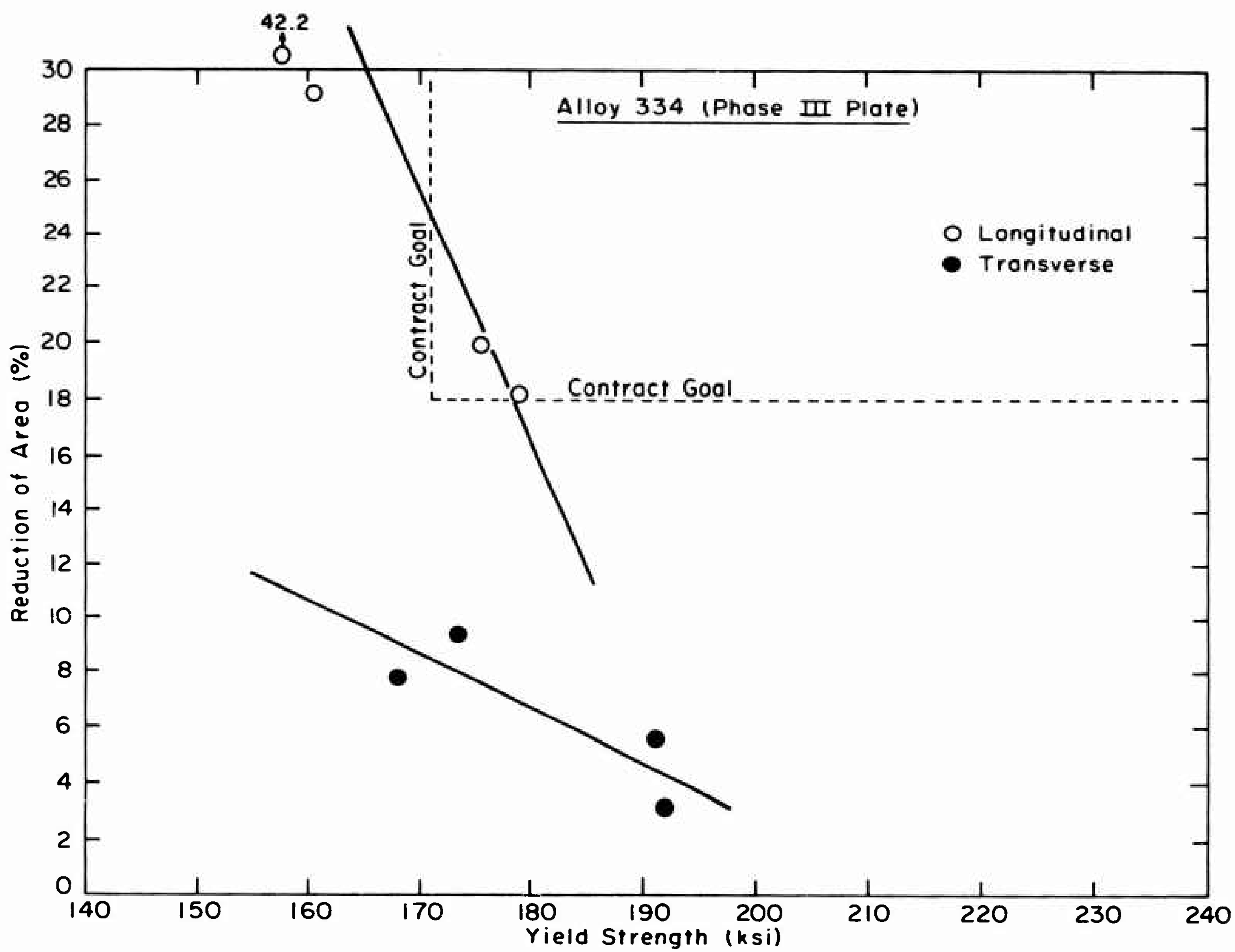


Figure 238. Alloy 334 (10Mo-6Cr-2.5Al), Phase III half-inch plate. Reduction of Area - Yield strength trend lines.

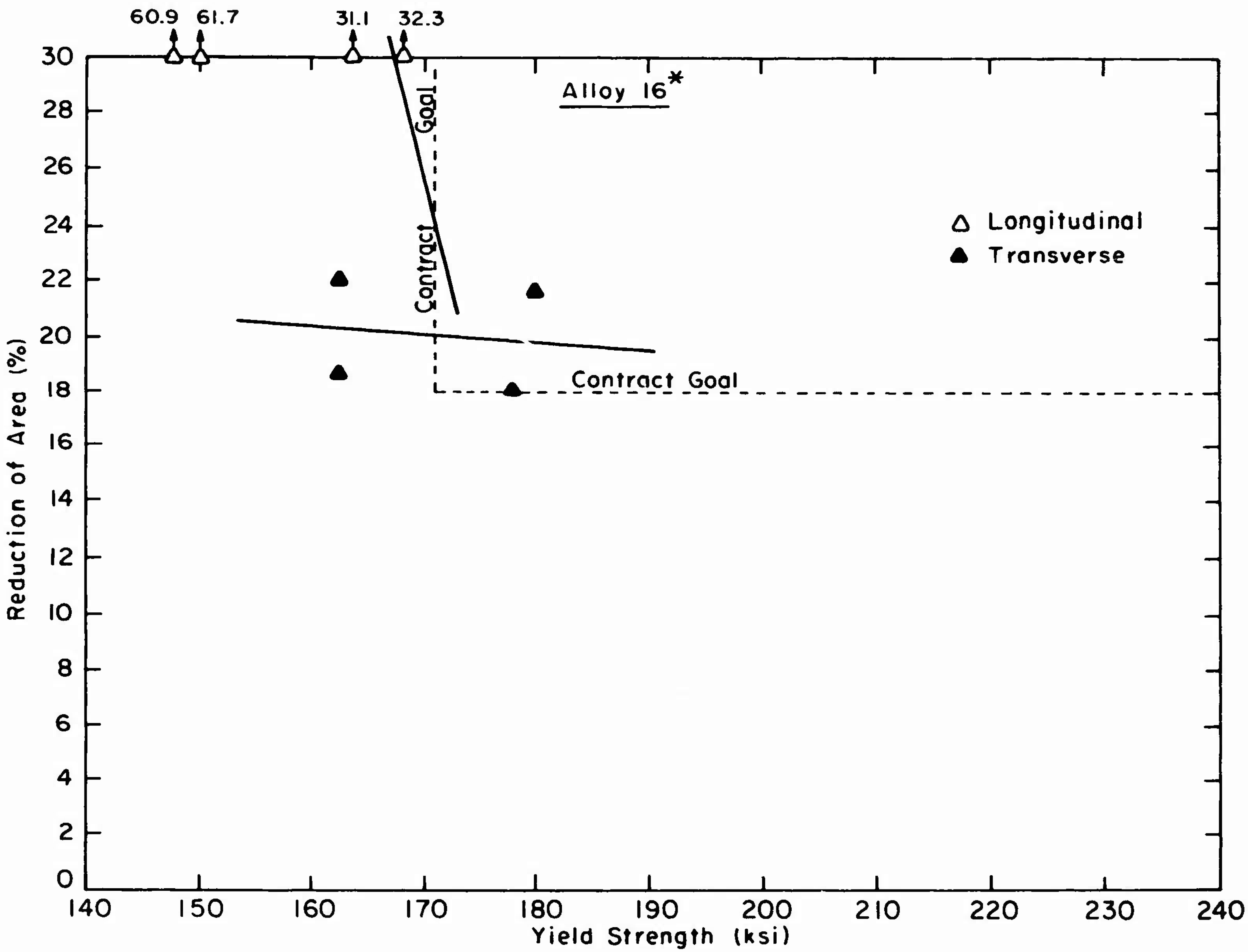


Figure 239. Alloy 16 (8Mo-4.5Cr-2.5Al). Half-inch plate. *Data developed under the NAVAIR program.(22) Reduction of Area - Yield strength trend lines.

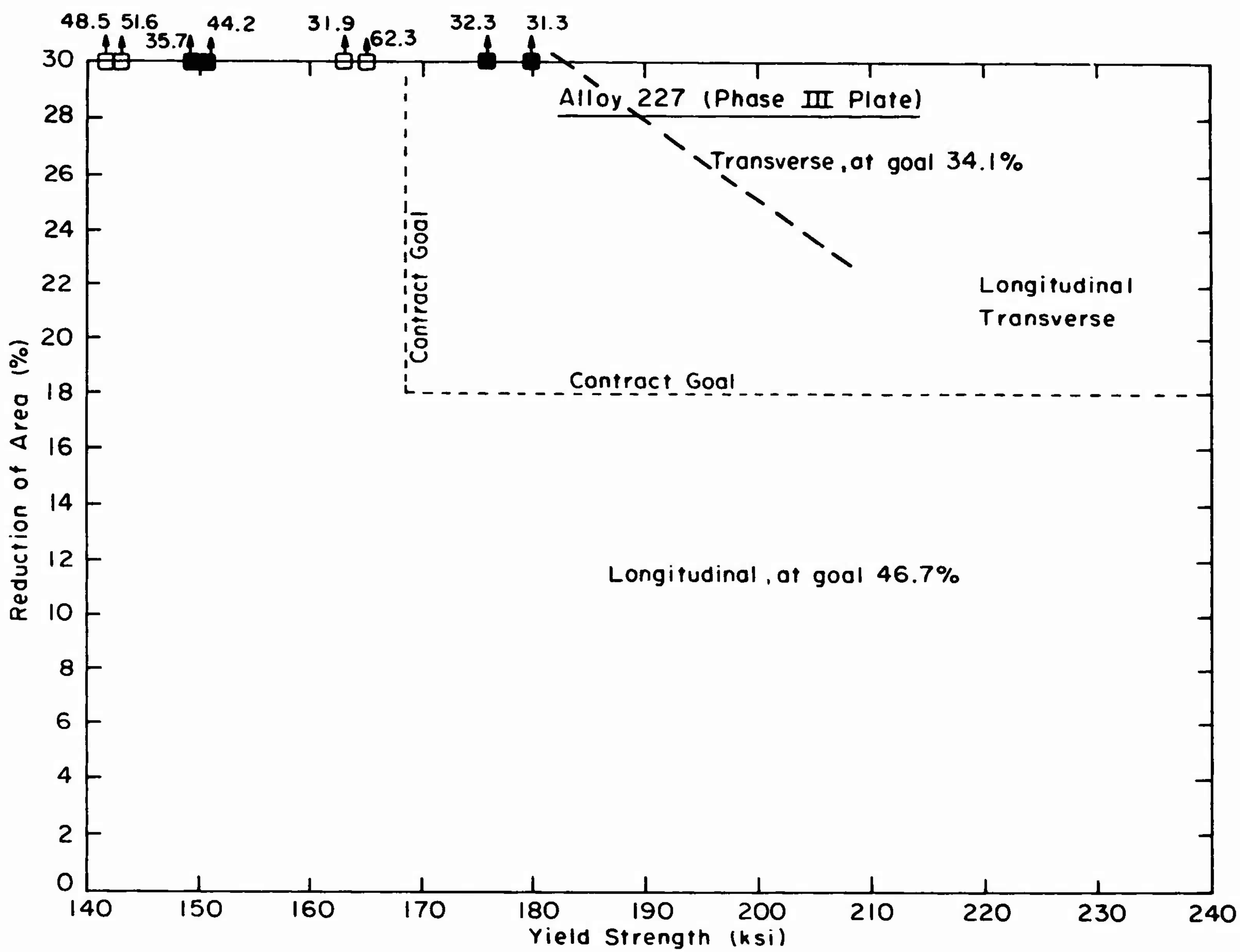


Figure 240. Alloy 227 (7Mo-4Cr-2.5Al). Phase III half-inch plate. Reduction of Area - Yield strength trend lines.

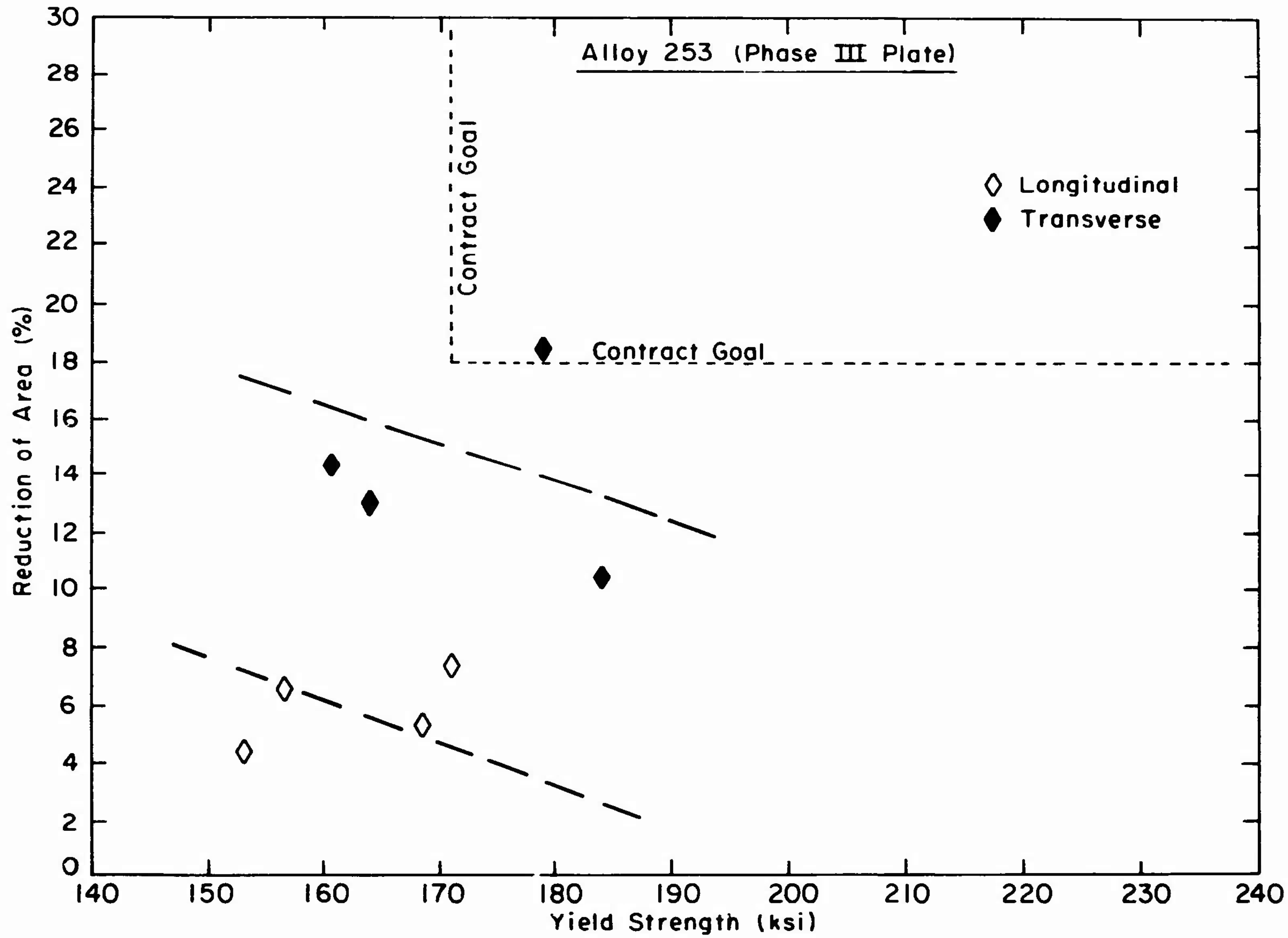


Figure 241. Alloy 253 (10Mo-8V-2.5Al). Phase III half-inch plate. Reduction of Area - Yield strength trend lines.

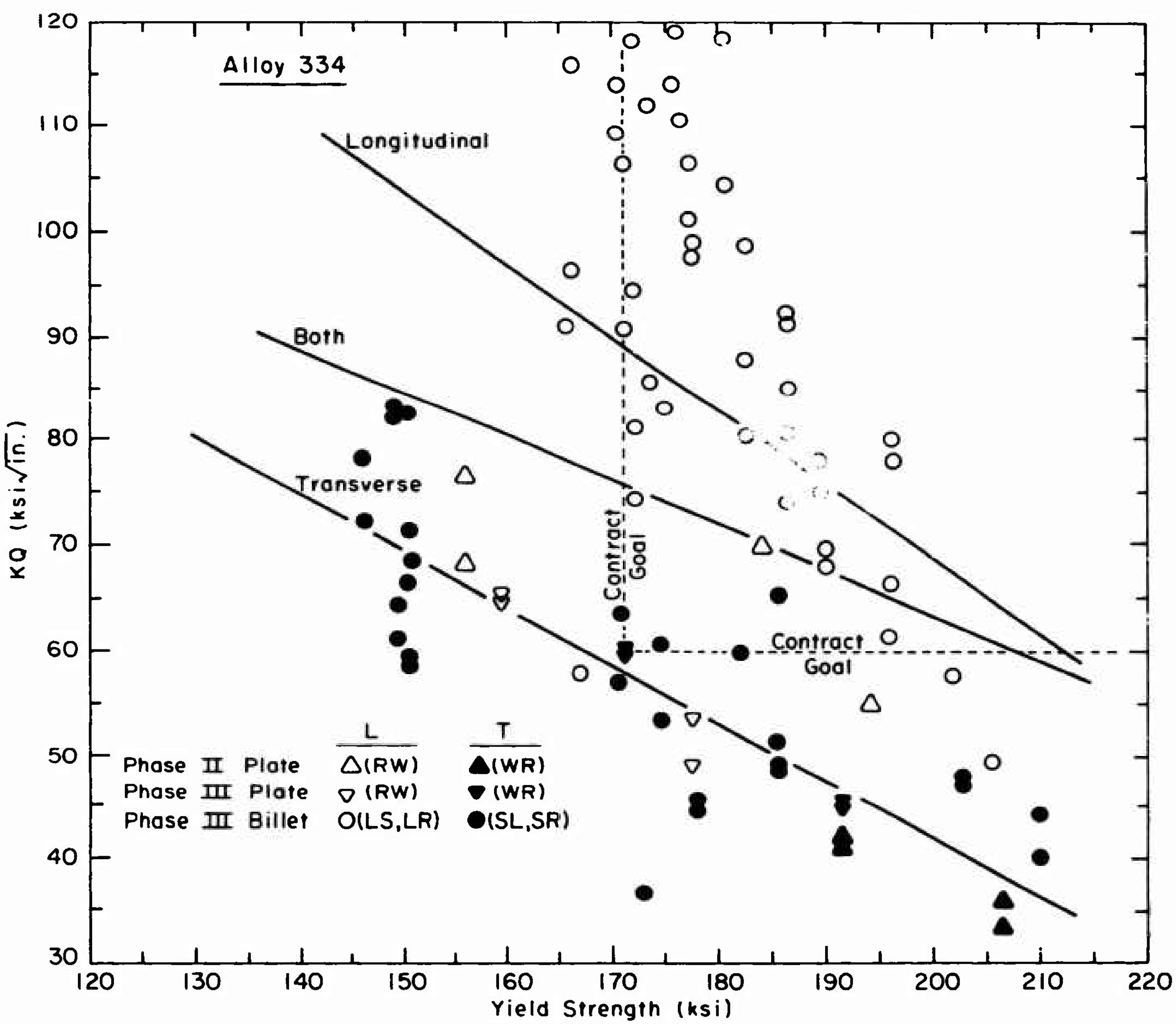


Figure 242. Alloy 334 (10Mo-6Cr-2.5Al). Overall alloy characteristic toughness (K_Q) - Yield strength trend lines.

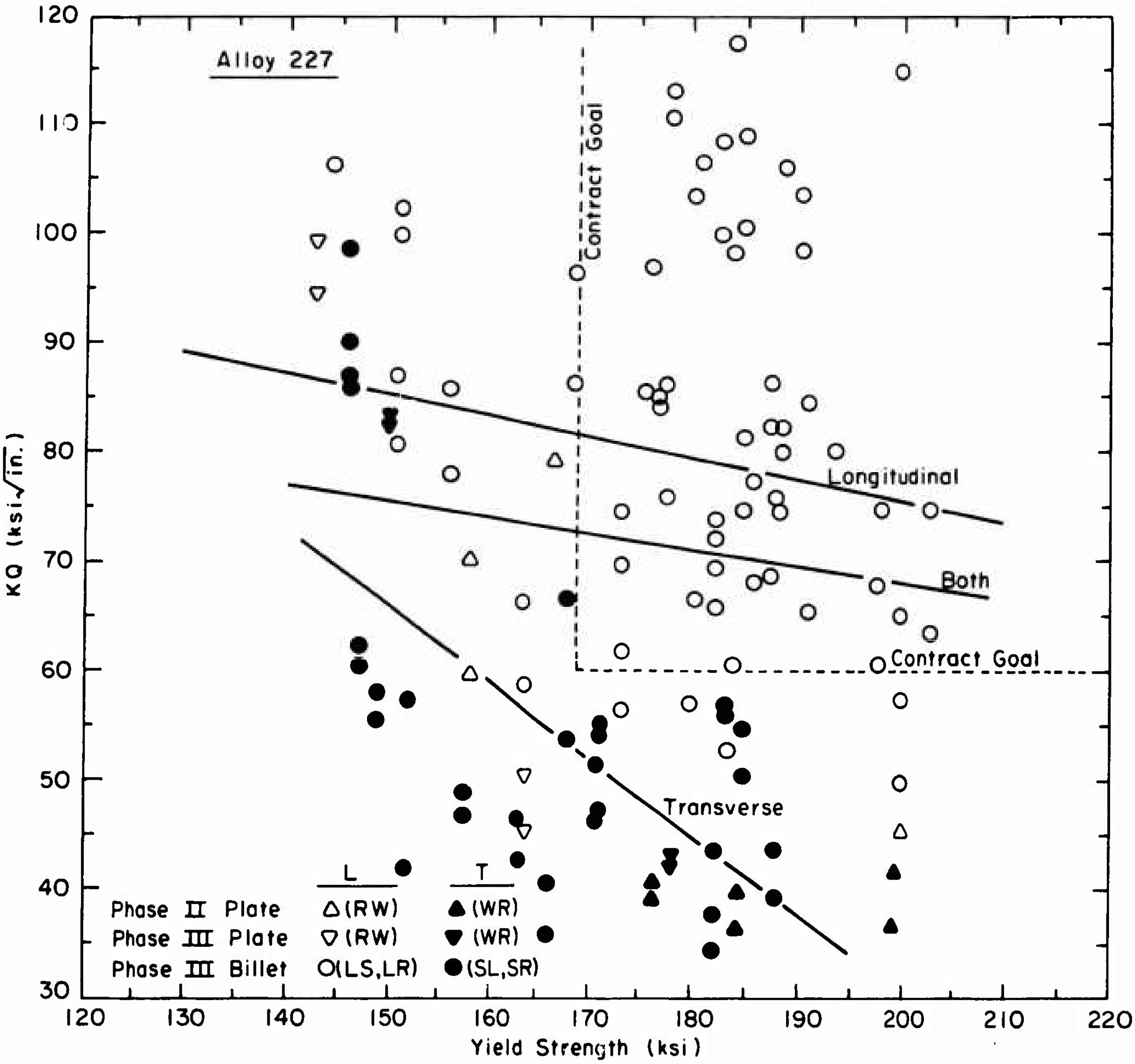


Figure 243. Alloy 227 (7Mo-4Cr-2.5Al). Overall alloy characteristic toughness (K_Q) - Yield strength trend lines.

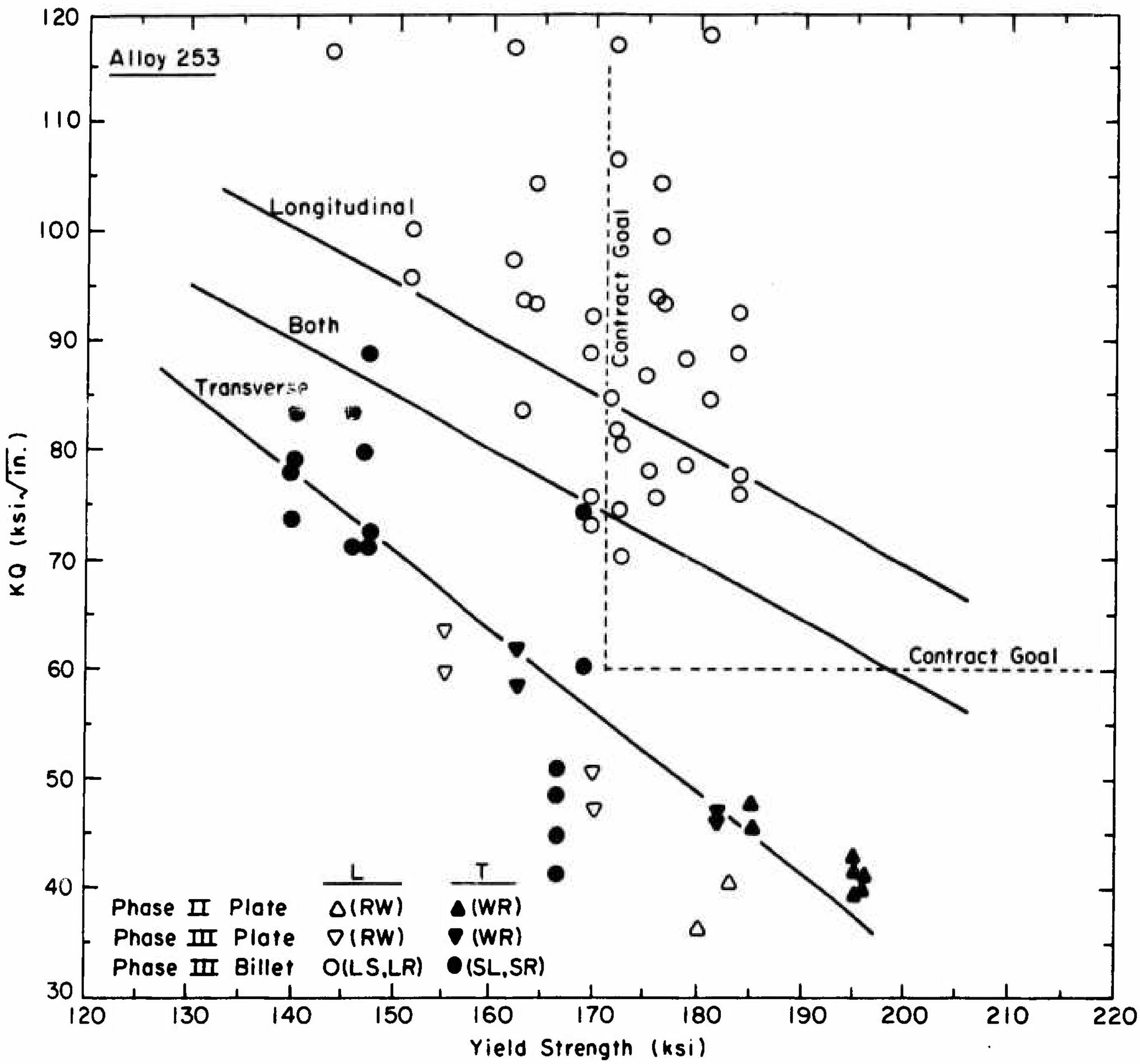


Figure 244. Alloy 253 (10Mo-8V-2.5Al). Overall alloy characteristic toughness (K_Q) Yield strength trend lines.

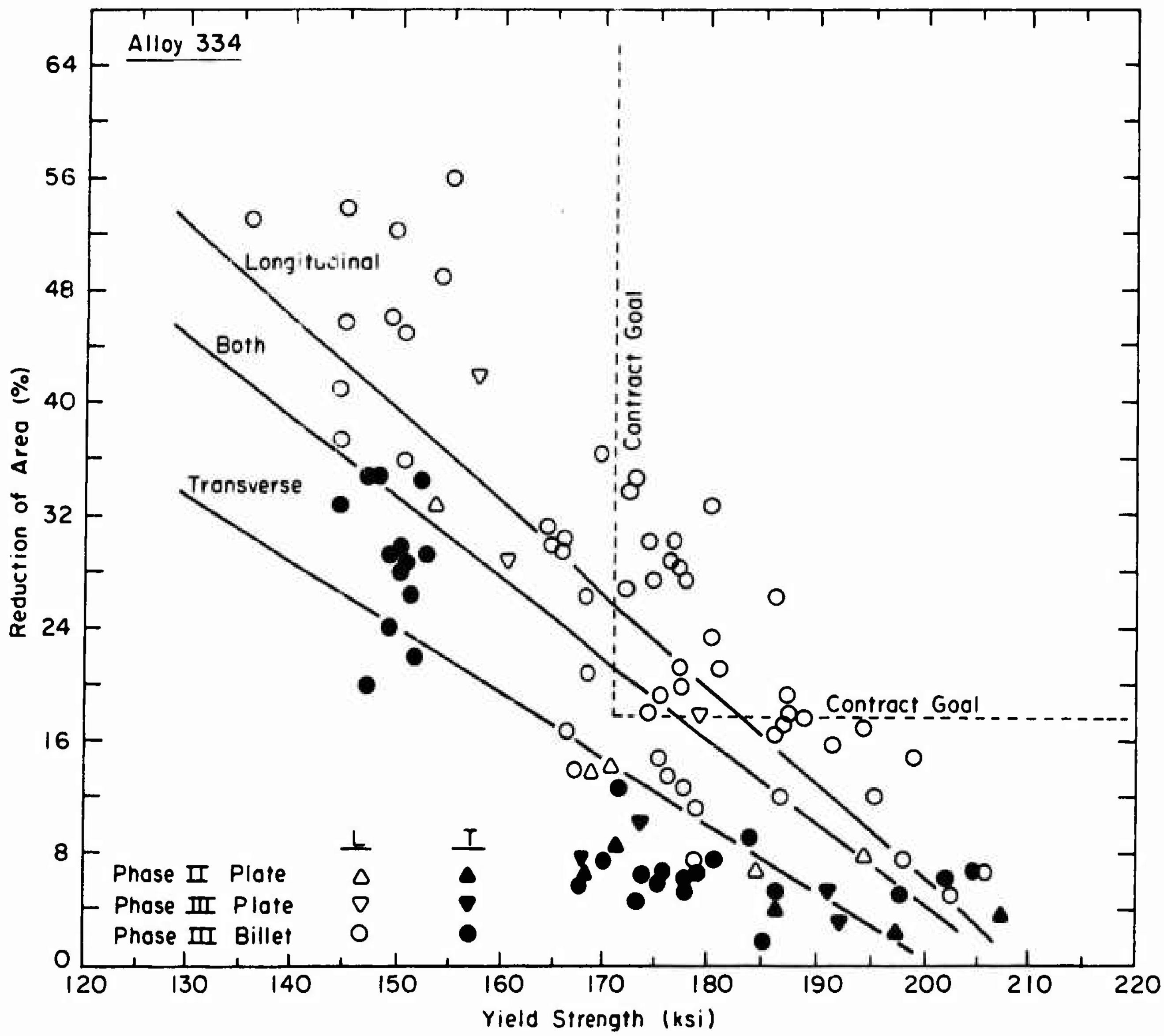


Figure 245. Alloy 334 (10Mo-6Cr-2.5Al). Overall alloy characteristic ductility (RA) - Yield strength trend lines.

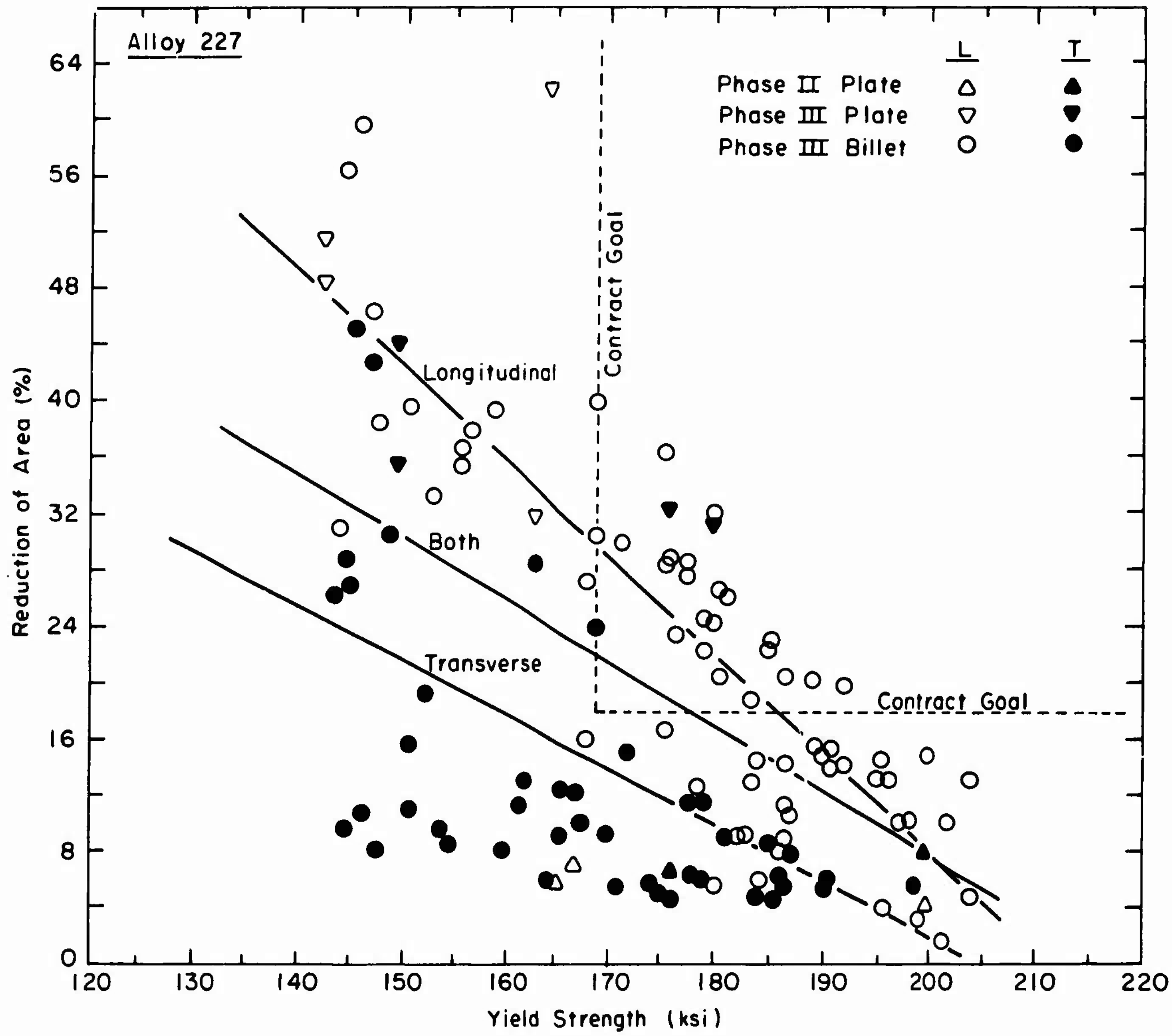


Figure 246. Alloy 227 (7Mo-4Cr-2.5Al). Overall alloy characteristic ductility (RA) Yield strength trend lines.

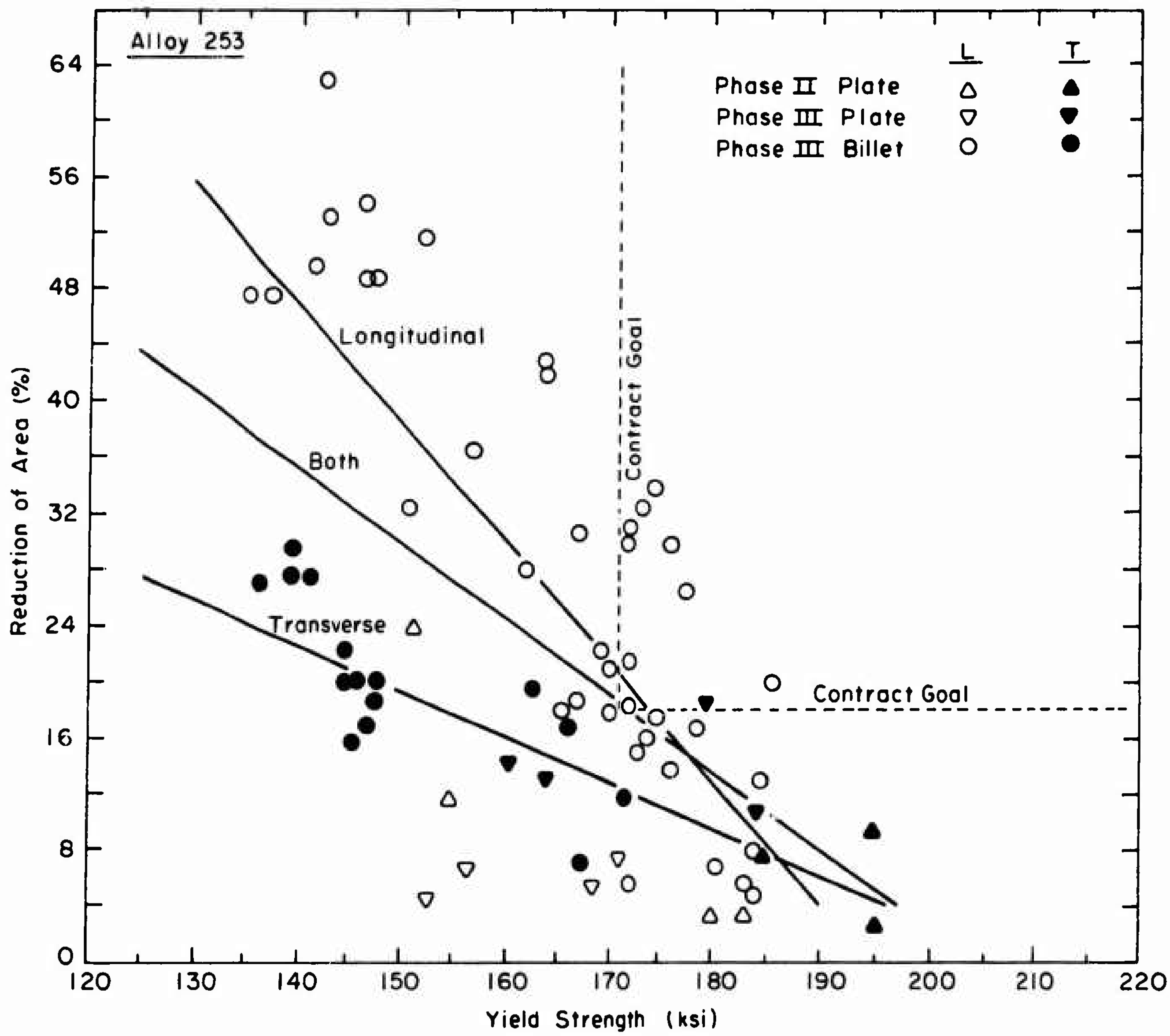


Figure 247. Alloy 253 (10Mo-8V-2.5Al). Overall alloy characteristic ductility (RA) - Yield strength trend lines.

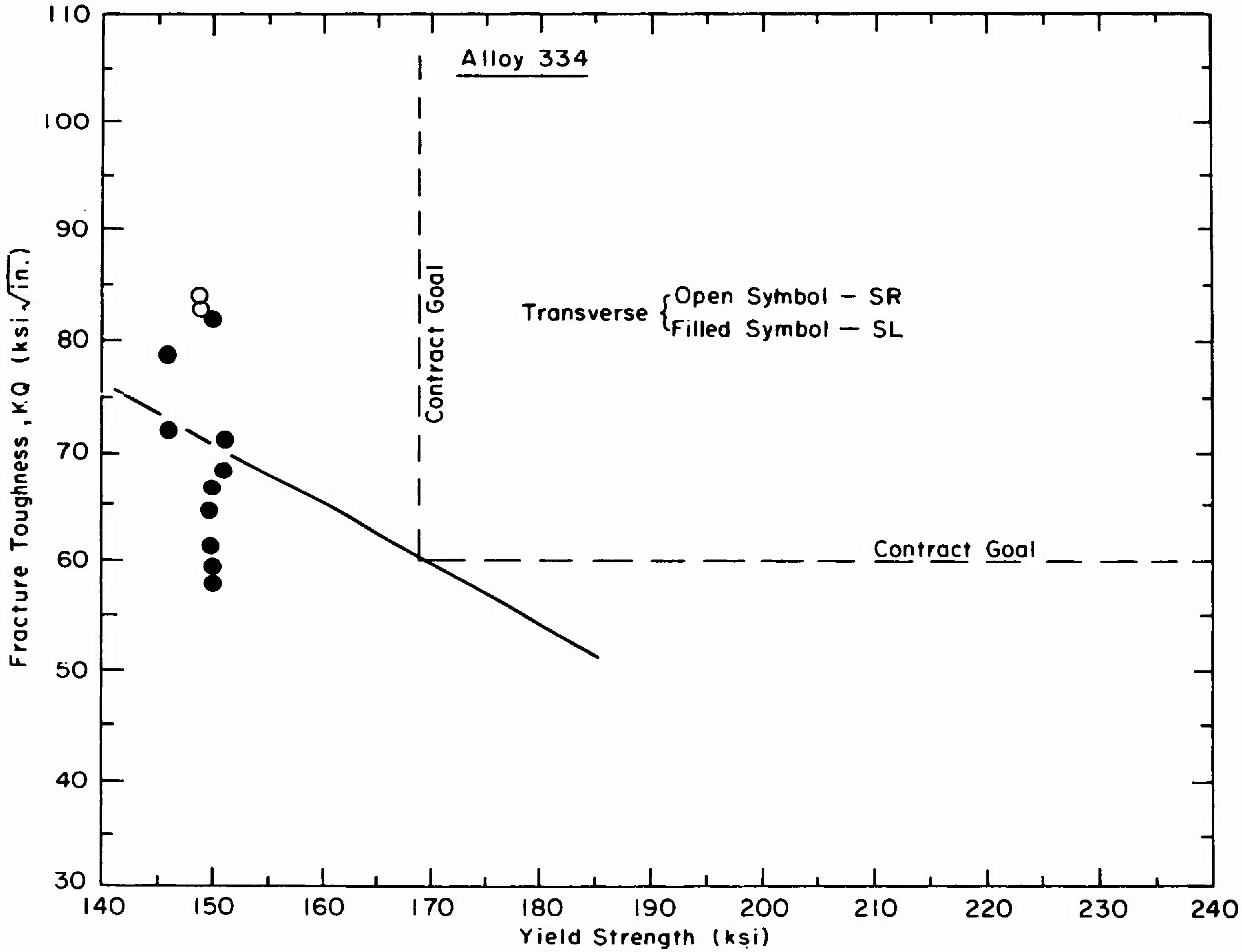


Figure 248. Alloy 334 (10Mo-6Cr-2.5Al). Transverse alloy characteristic toughness (K_Q) - Yield strength trend line for "optimum" heat-treatment.

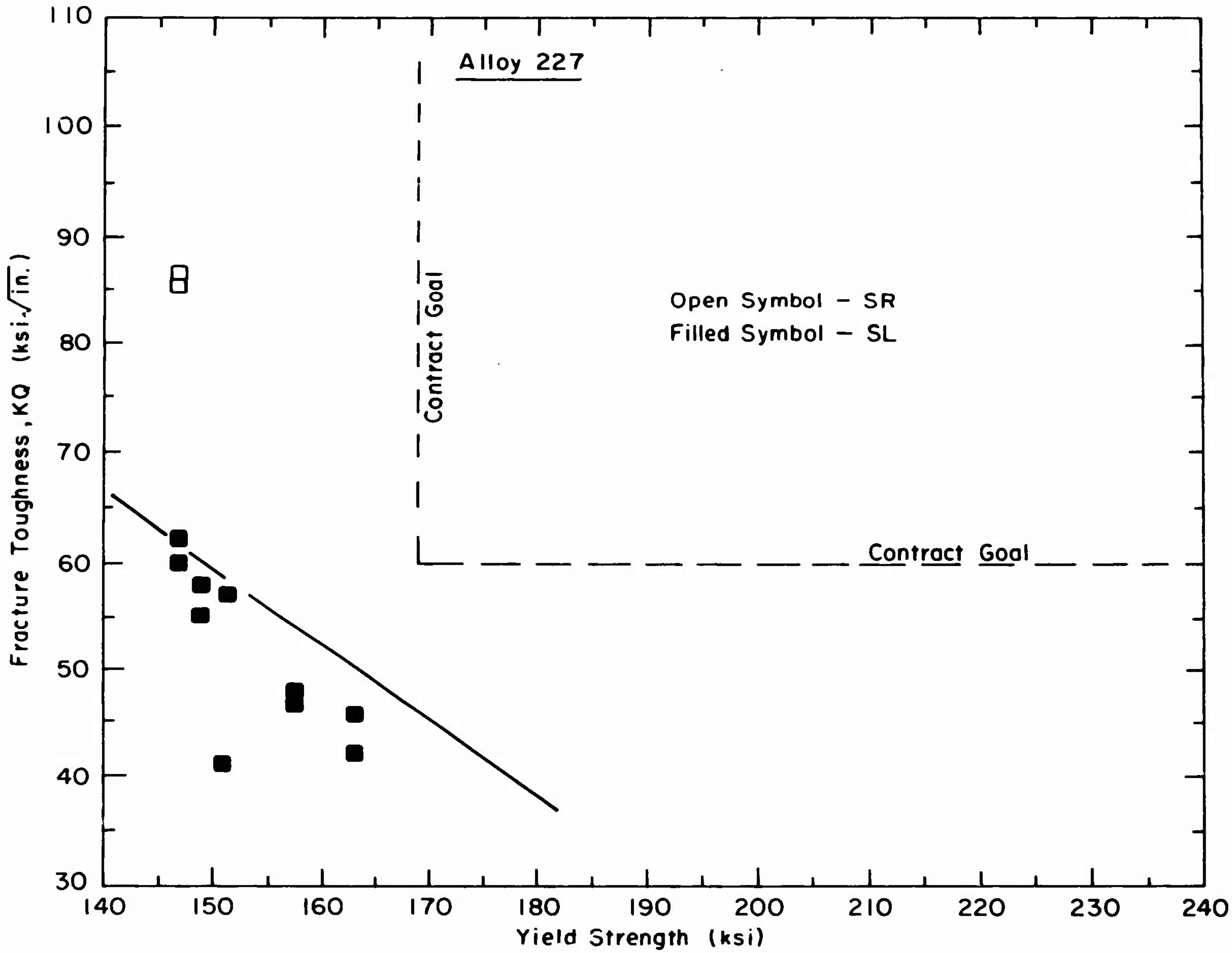


Figure 249. Alloy 227 (7Mo-4Cr-2.5Al). Transverse alloy characteristic toughness (K_Q) - Yield strength trend line for "optimum" heat-treatment.

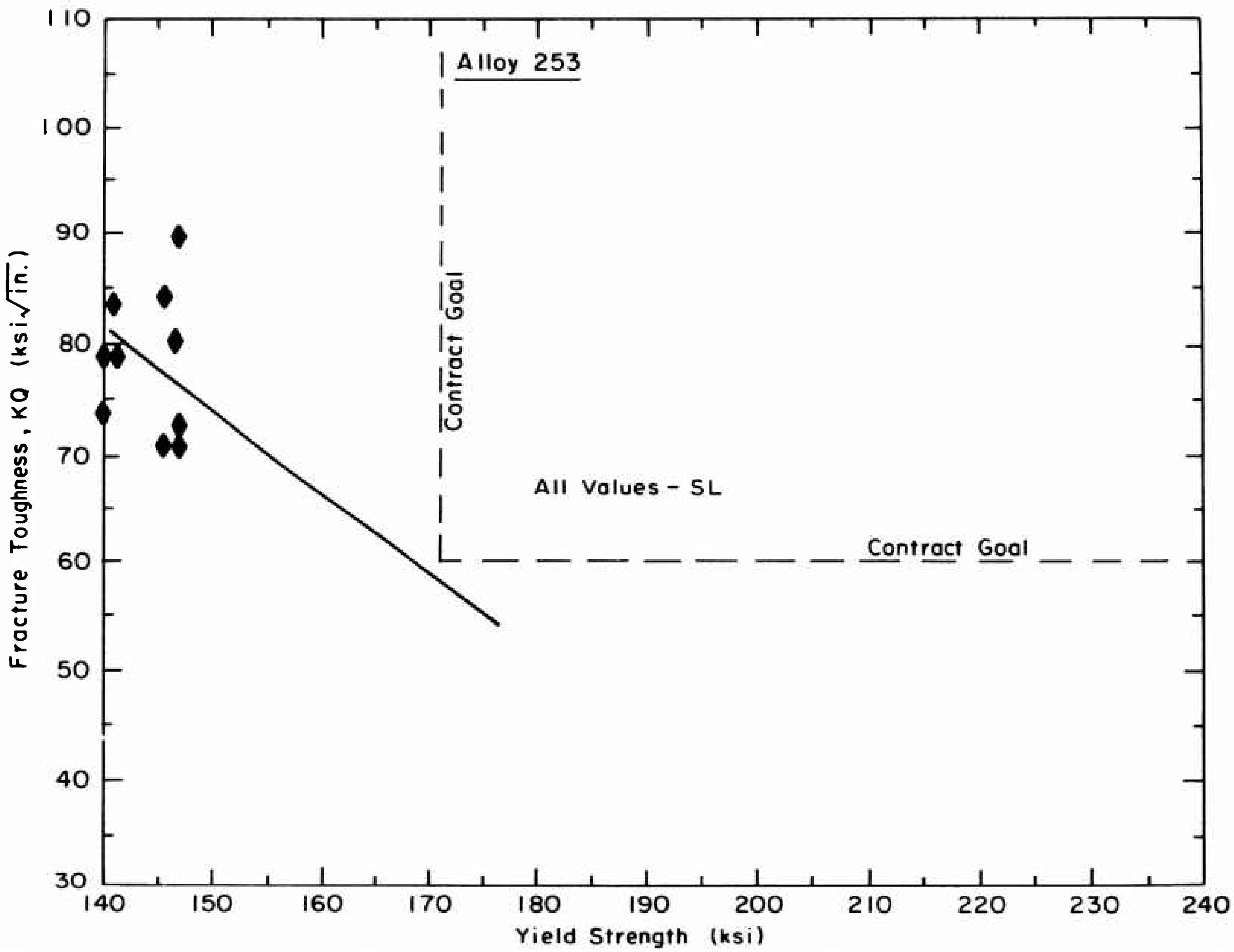


Figure 250. Alloy 253 (10Mo-8V-2.5Al). Transverse alloy characteristic toughness (K_Q) - Yield strength trend line for "optimum" heat-treatment.

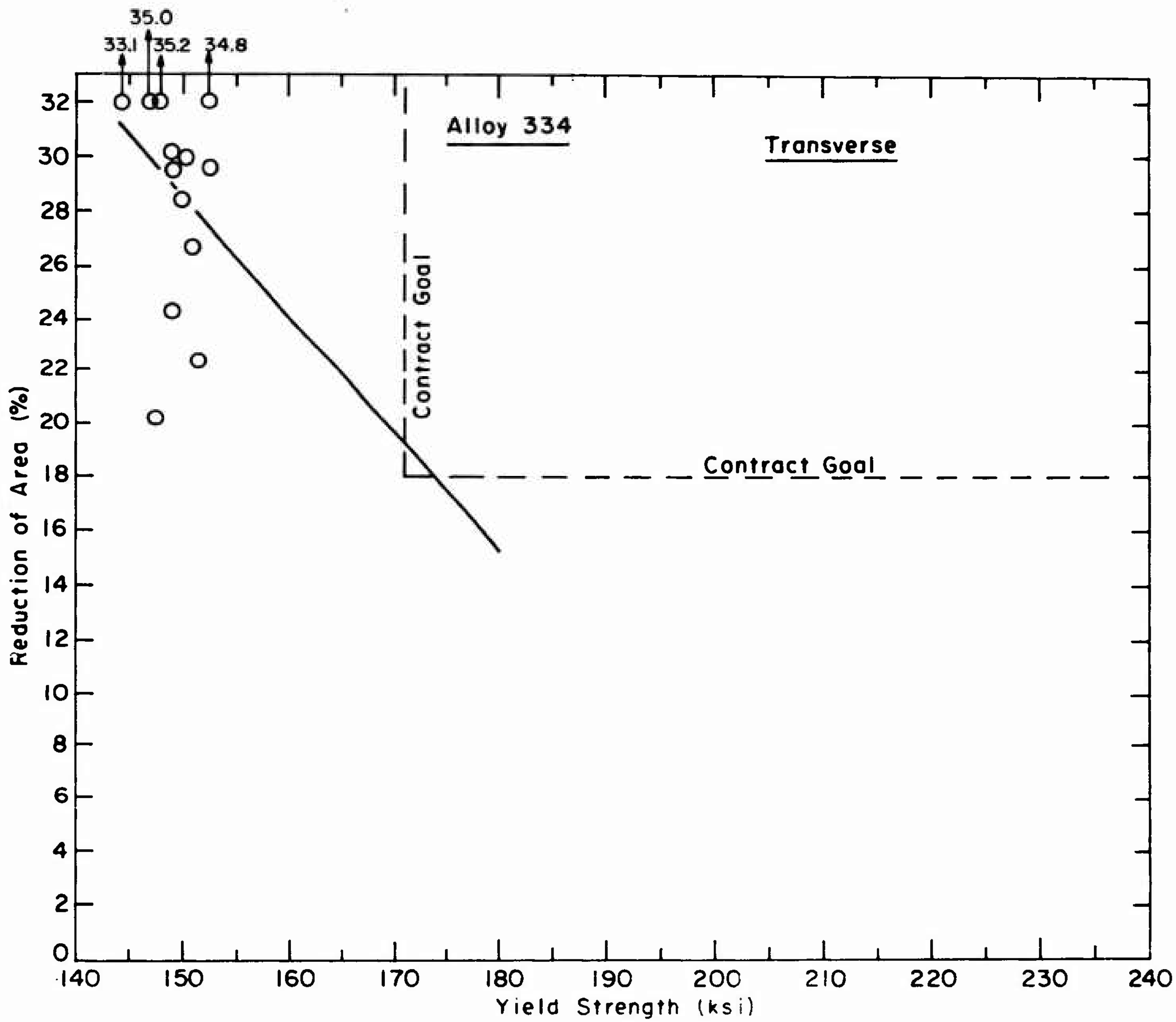


Figure 251. Alloy 334 (10Mo-6Cr-2.5Al). Transverse alloy characteristic reduction of area (RA) - Yield strength trend line for "optimum" heat-treatment.

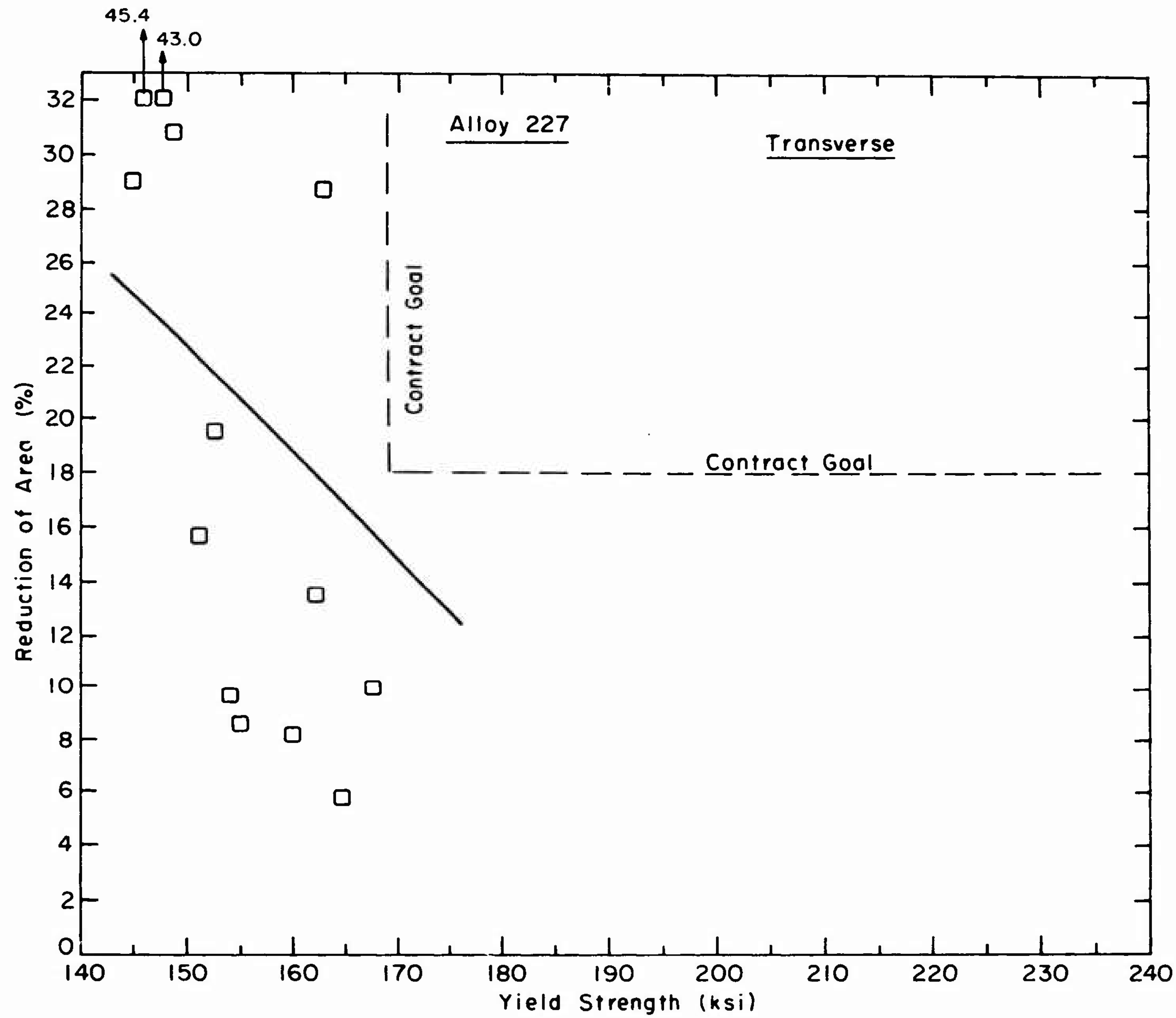


Figure 252. Alloy 227 (7Mo-4Cr-2.5Al). Transverse alloy characteristic reduction of area (RA) - Yield strength trend line for "optimum" heat-treatment.

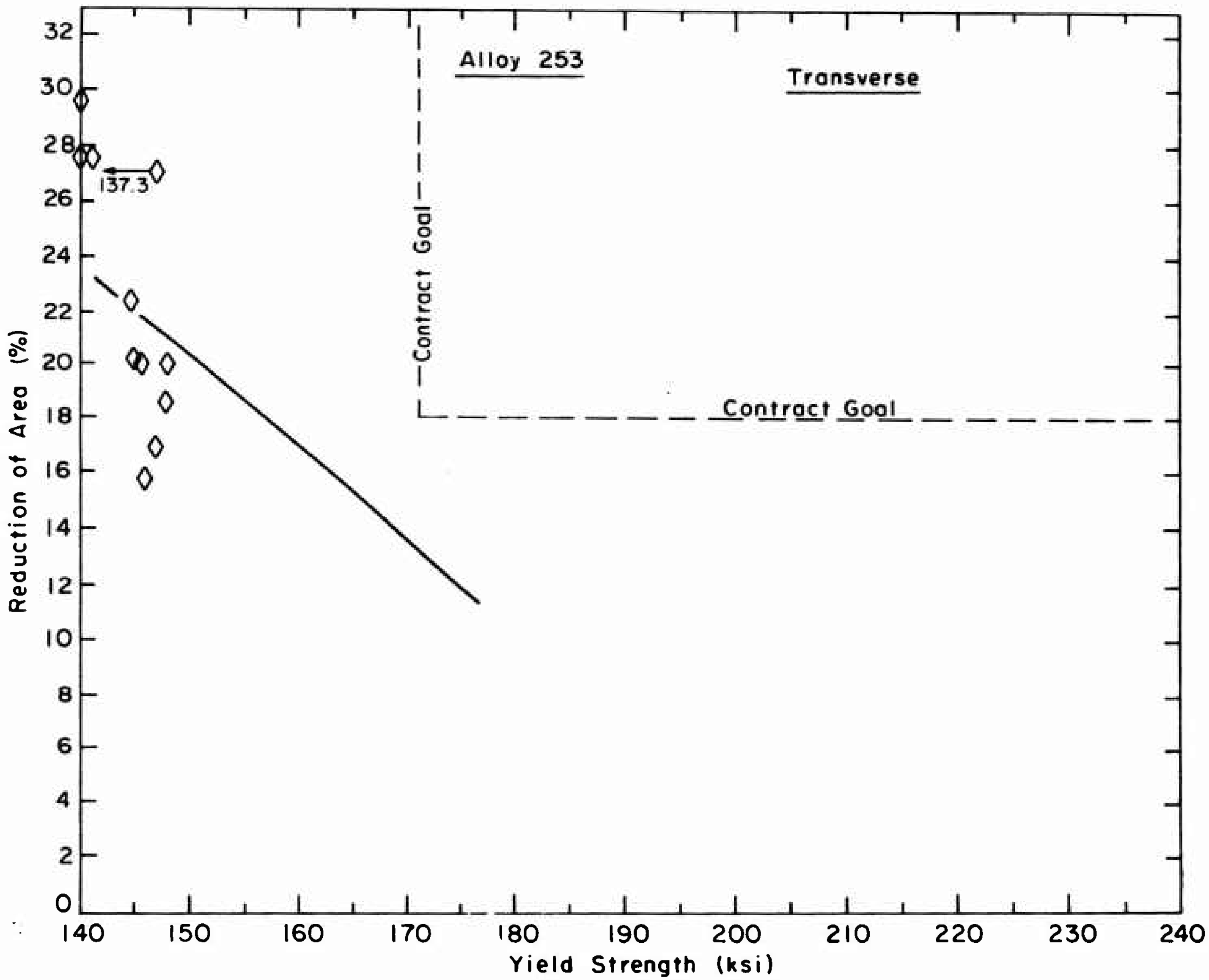


Figure 253. Alloy 253 (10Mo-8V-2.5Al). Transverse alloy characteristic reduction of area (RA) - Yield strength trend line for "optimum" heat-treatment.

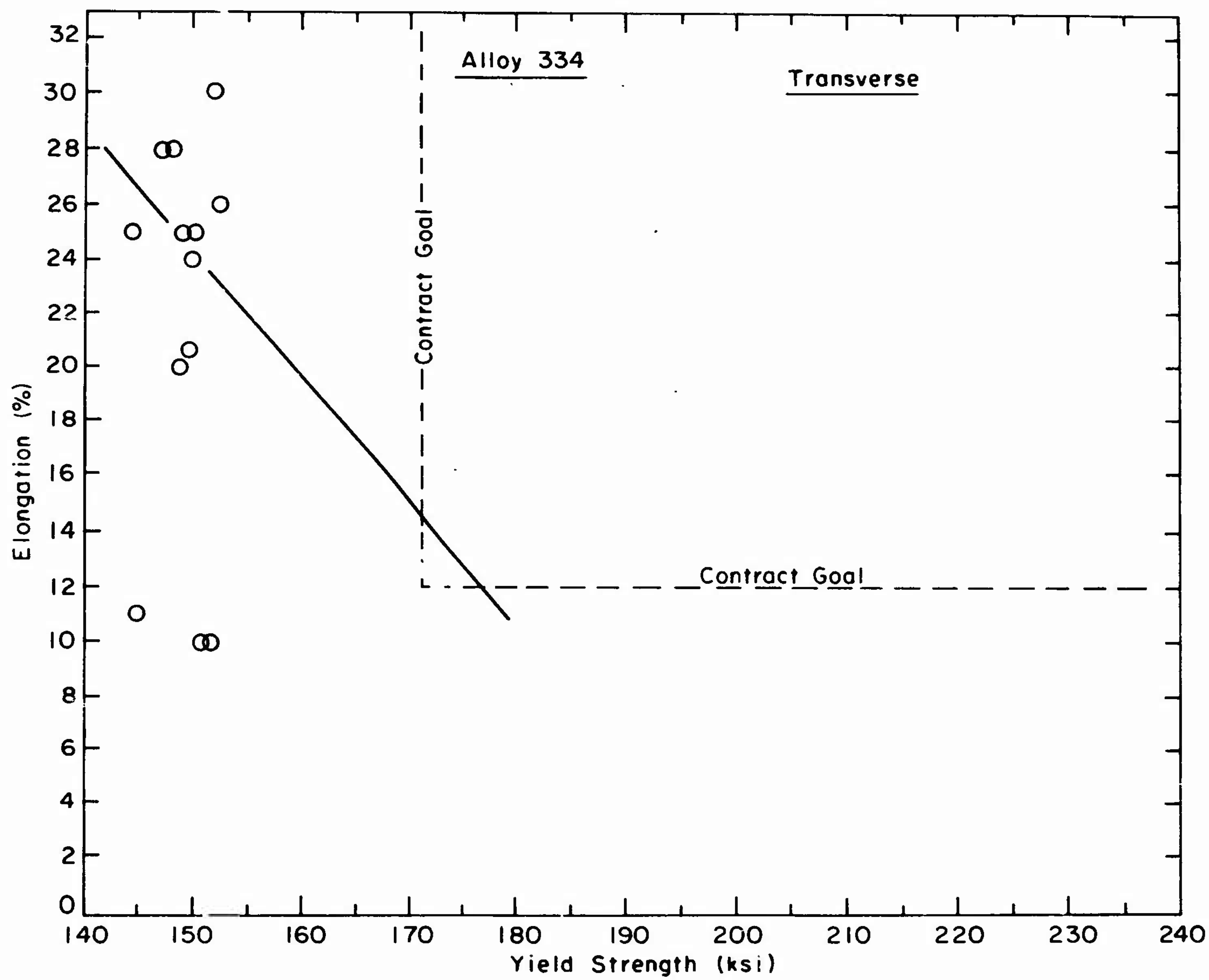


Figure 254. Alloy 334 (10Mo-6Cr-2.5Al). Transverse alloy characteristic elongation - Yield strength trend line for "optimum" heat-treatment.

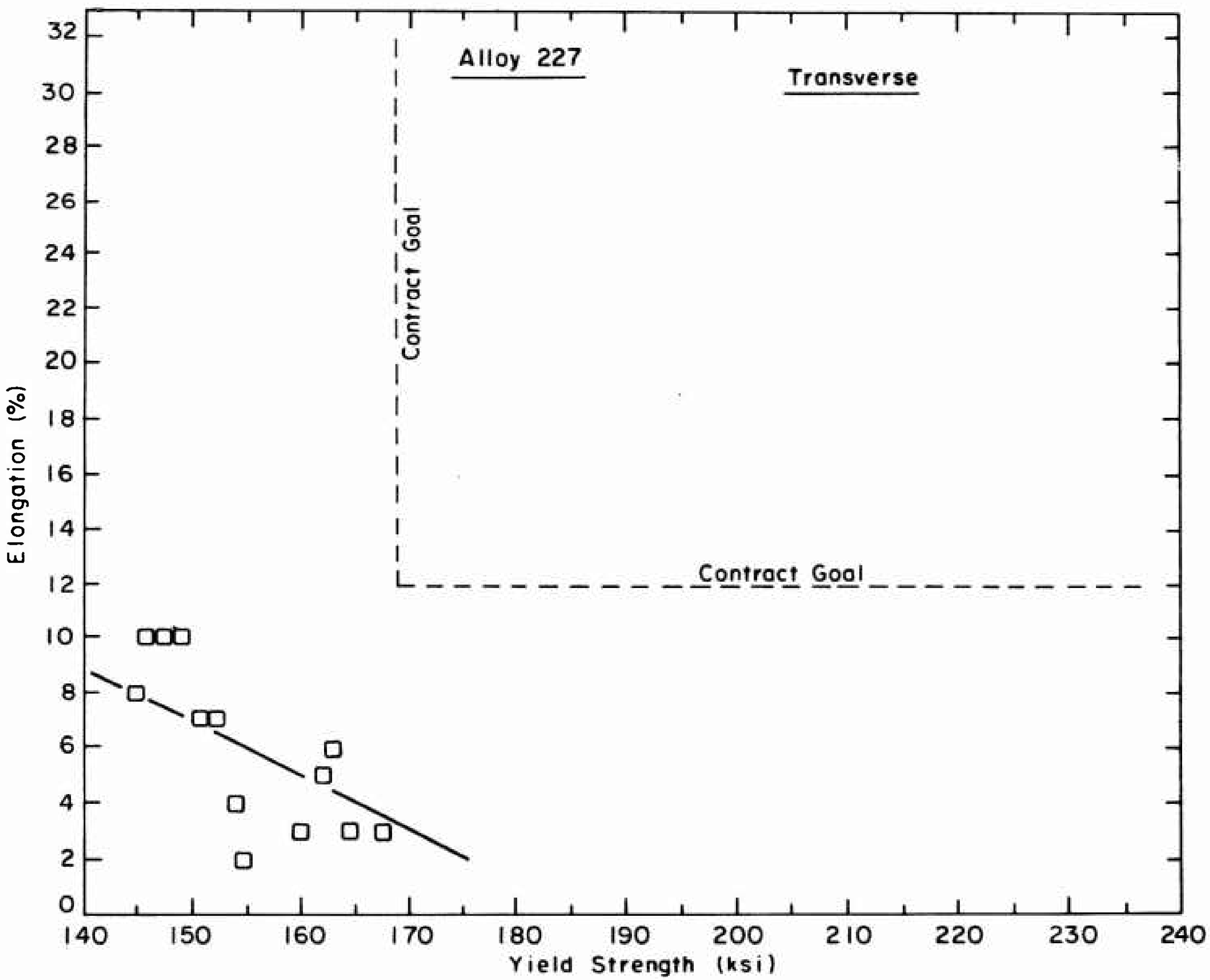


Figure 255. Alloy 227 (7Mo-4Cr-2.5Al). Transverse alloy characteristic elongation - Yield strength trend line for "optimum" heat-treatment.

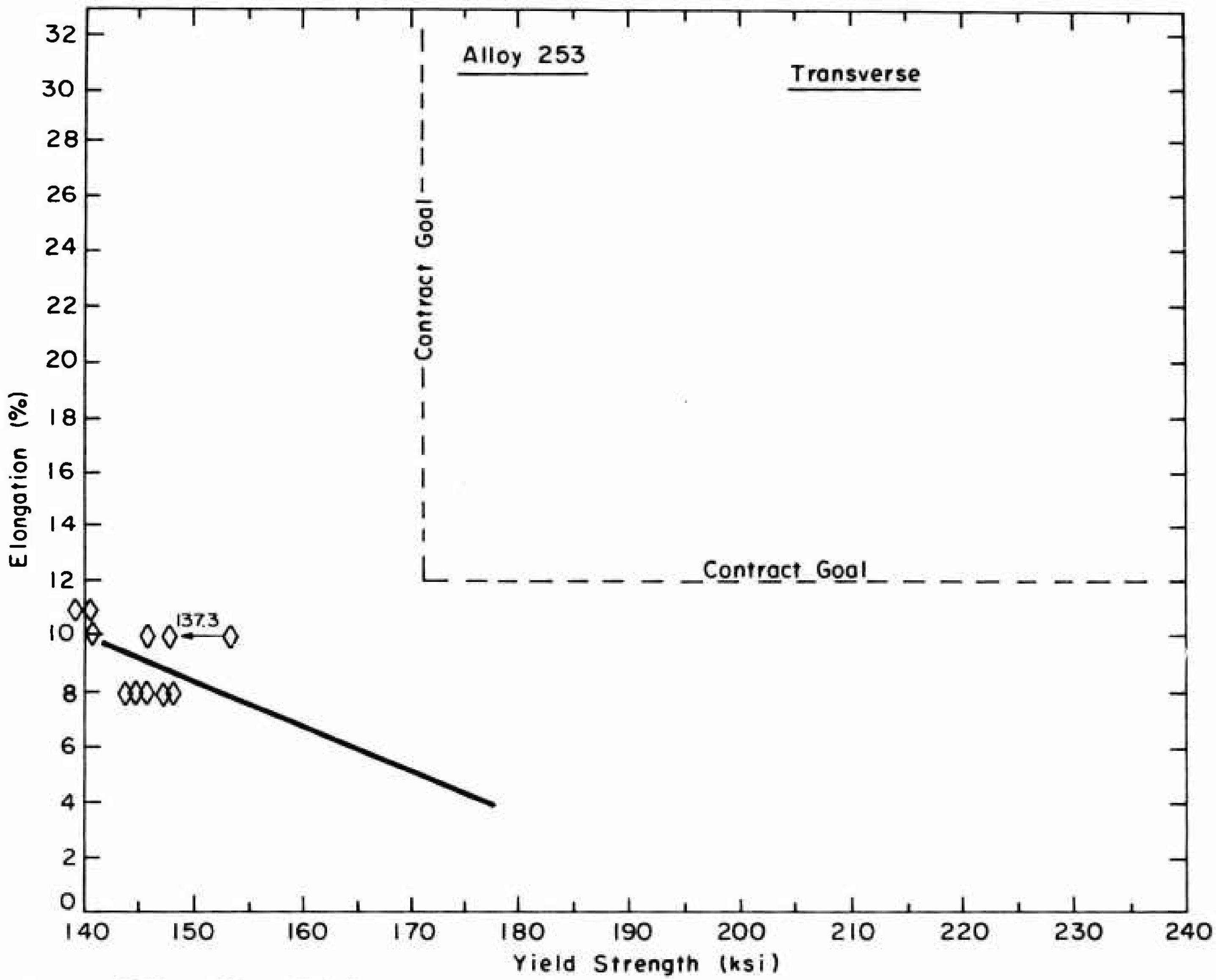


Figure 256. Alloy 253 (10Mo-8V-2.5Al). Transverse alloy characteristic elongation - Yield strength trend line for "optimum" heat-treatment.

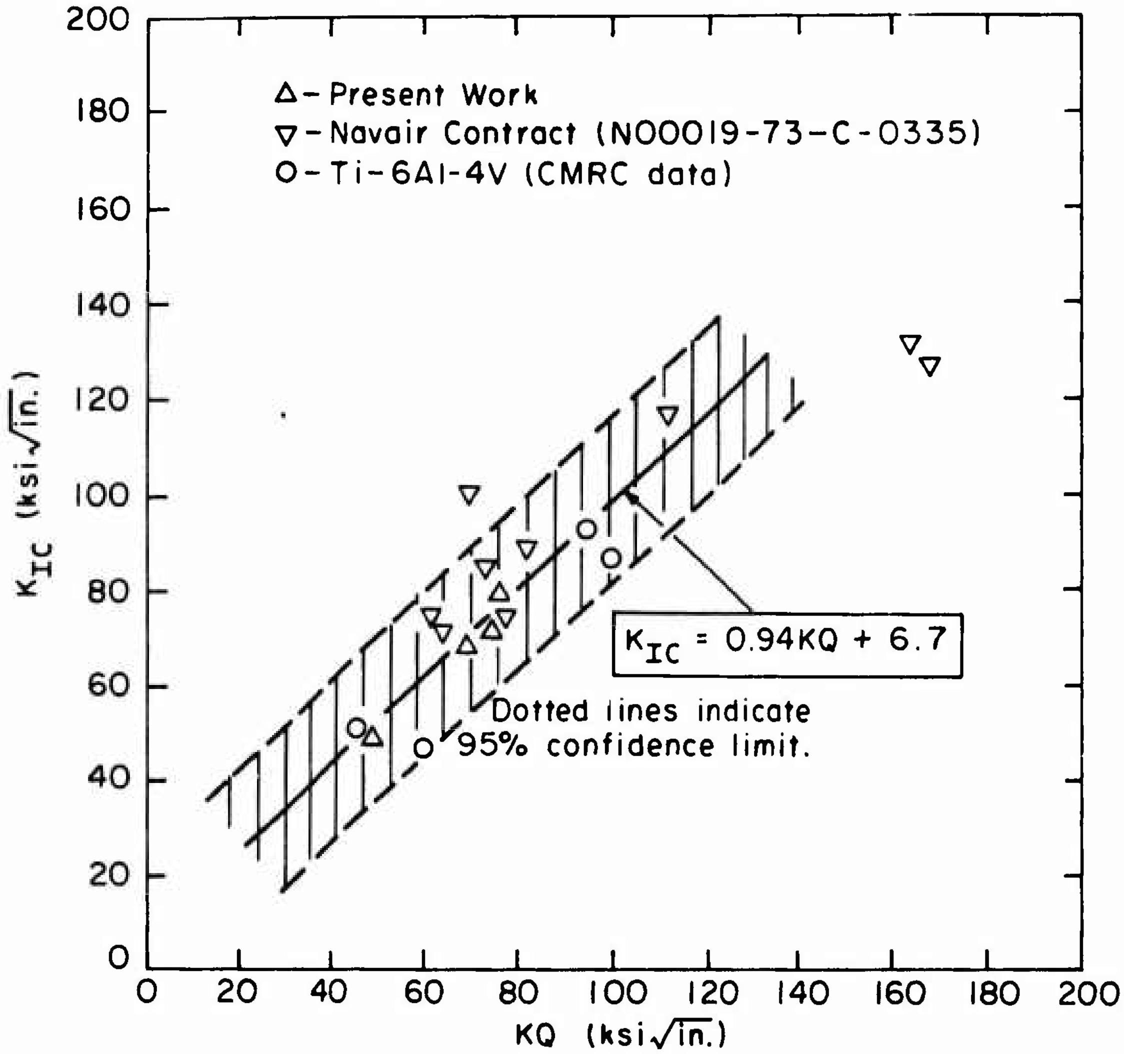


Figure 257. Relationship of K_{Ic} to K_Q under present contract and parallel investigations.(22,23) K_{Ic} determined from valid test (see Appendix H), K_Q from slow bend pre-cracked Charpy samples. Each point is the average of at least two values for each parameter.

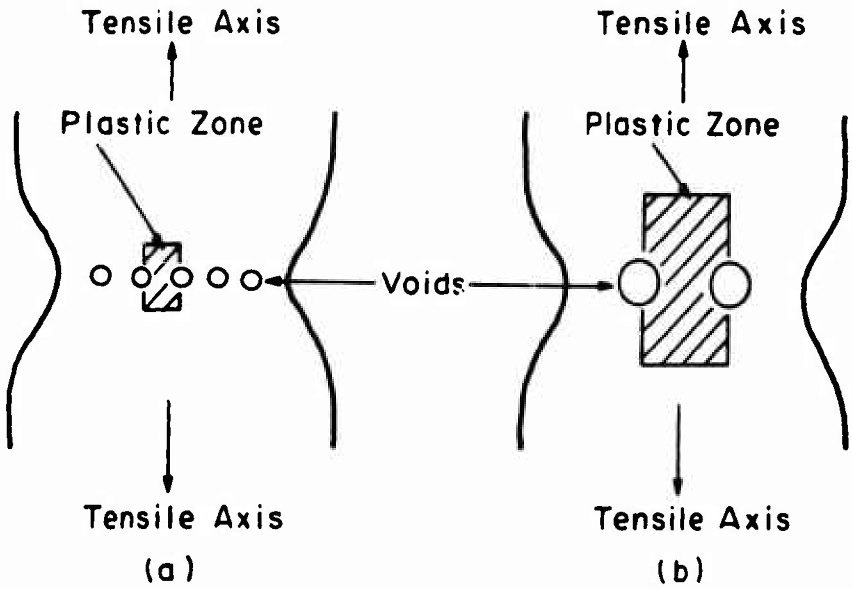


Figure 258. Schematic representation of void formation and associated plastically deformed zone as a result of applied tensile stress. The total plastic deformation with (a) many closely spaced voids is less than that with (b) few widely spaced voids, resulting in greater macroscopic ductility in the latter case.

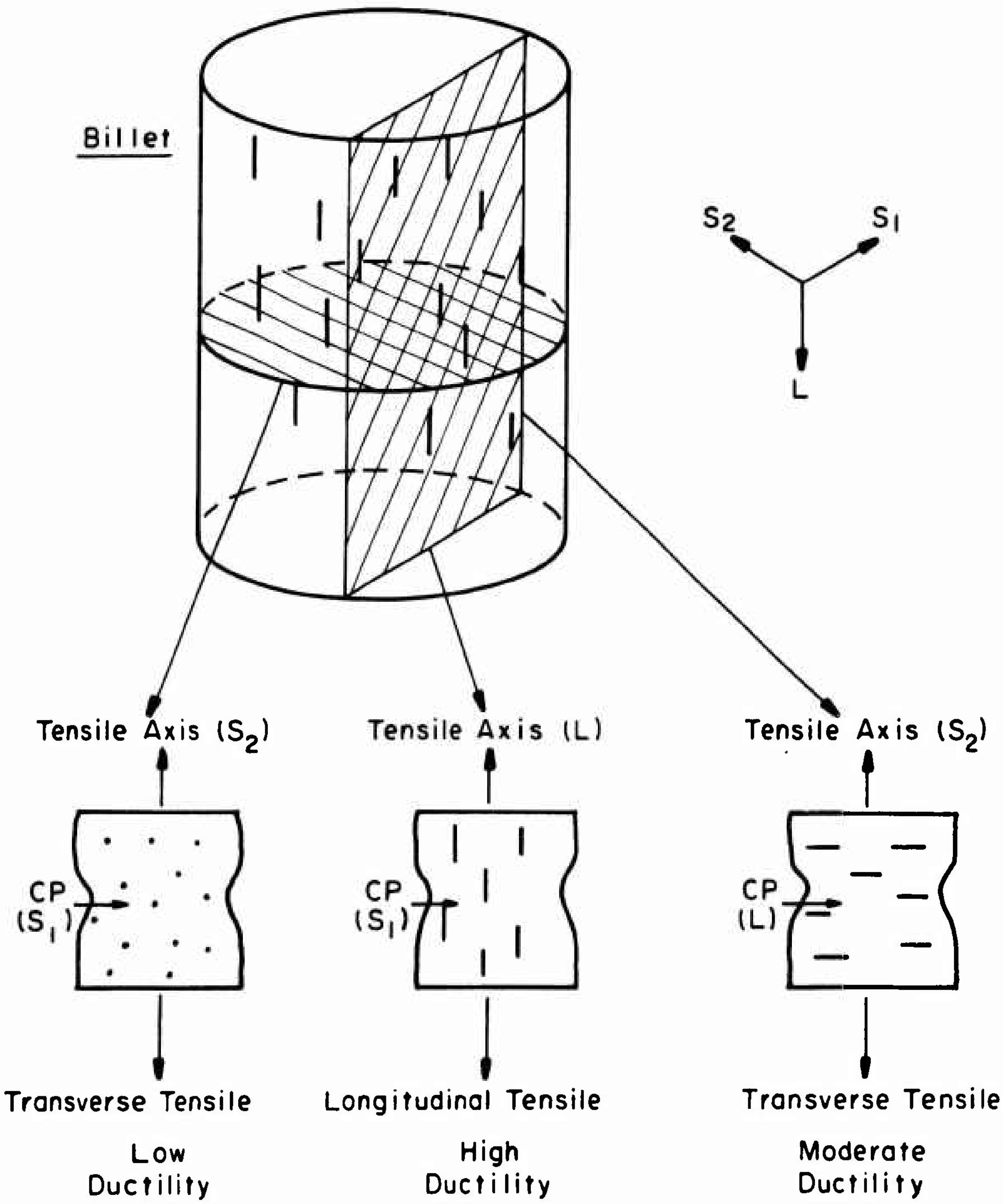


Figure 259. Schematic representation of relationship of ductility directionality to lenticular voids formed in a billet during tensile stress. CP is crack path extension direction. Longitudinal ductility is predicted to be significantly higher than transverse ductility.

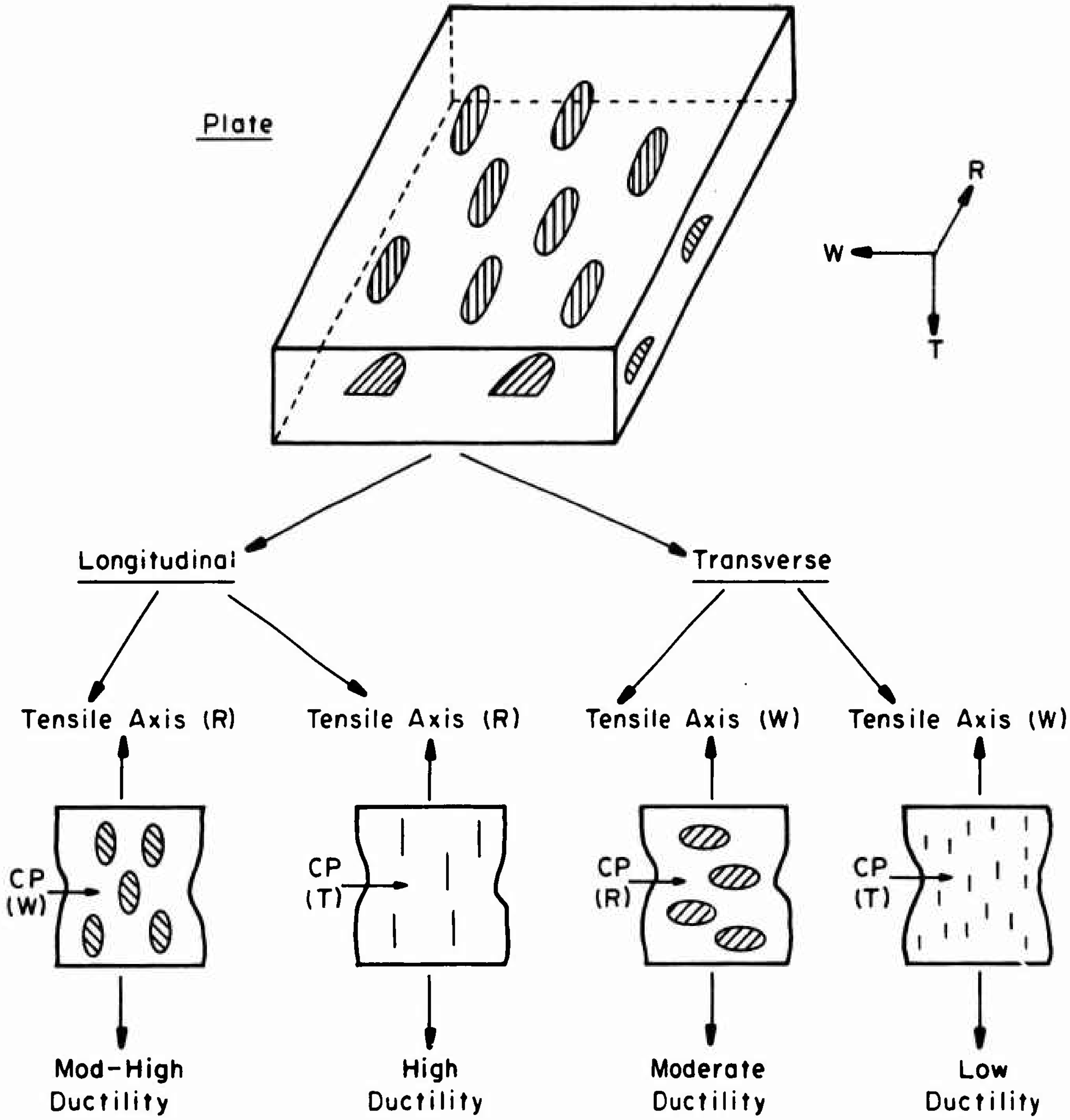


Figure 260. Schematic representation of relationship of ductility directionality to disc-like voids formed in plate during tensile stress. CP is crack path extension direction. Longitudinal ductility is predicted to be somewhat higher than transverse ductility.

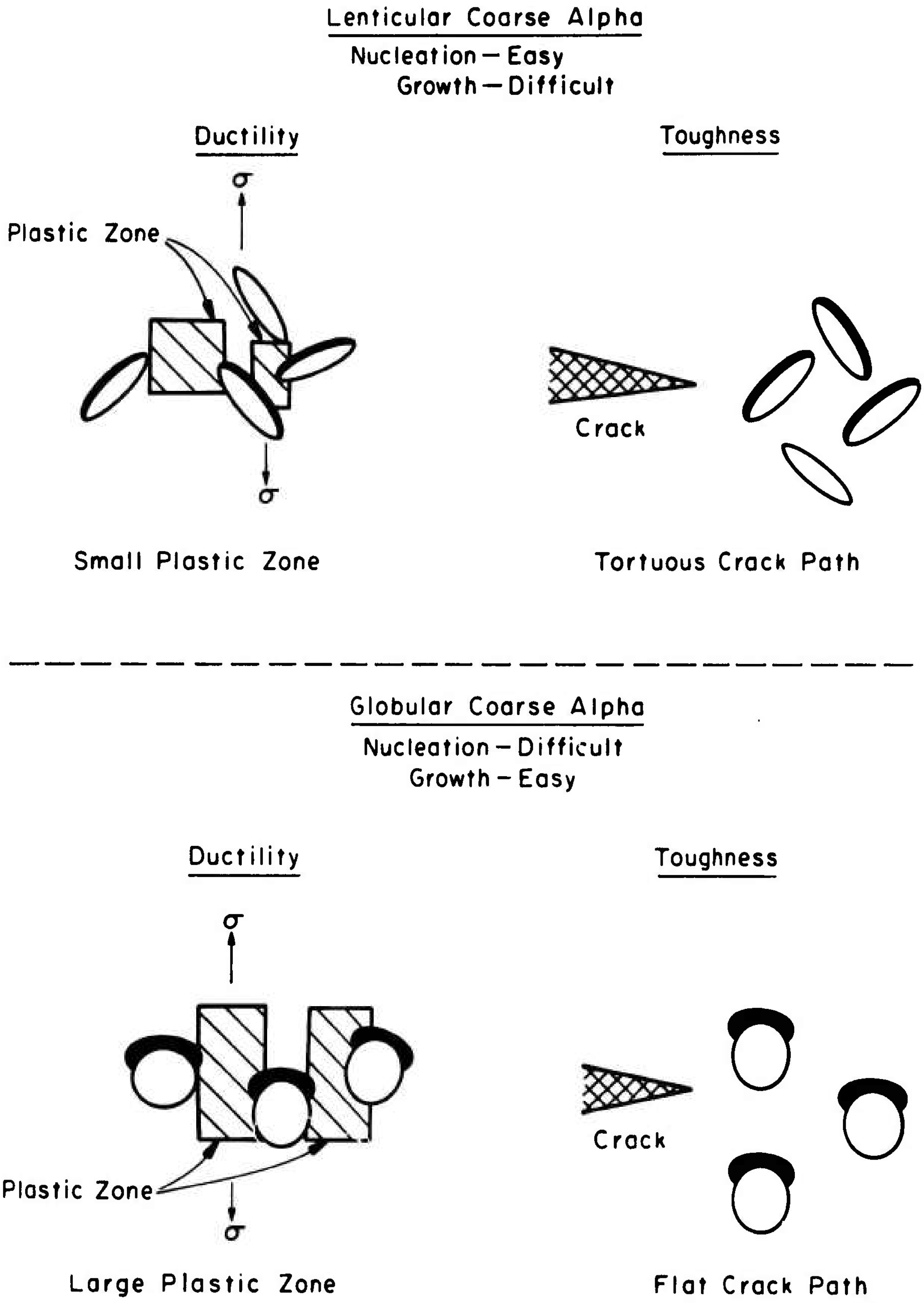


Figure 261. Schematic representation of effect of coarse alpha shape on ductility and toughness. For a given volume fraction of coarse alpha the total plastic zone is greater for globular alpha. However, for a propagating crack, the tortuosity factor for lenticular alpha overcomes this effect. Voids are shown as black regions.

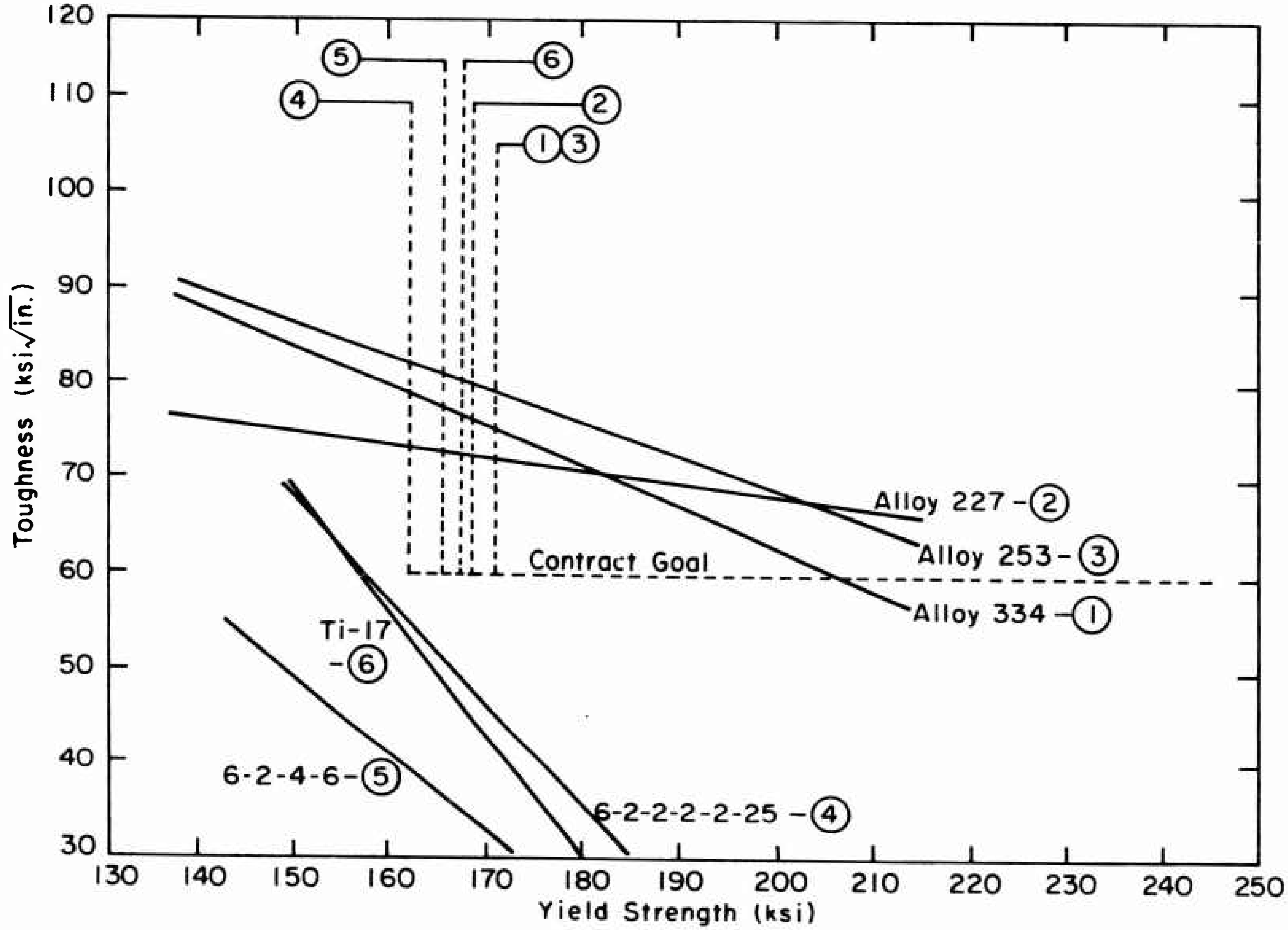


Figure 262 - Toughness-yield strength characteristic alloy trend lines for present contract alloys and experimental and semi-commercial deep hardenable alloys. Goal properties for each alloy are density normalized (number code above).

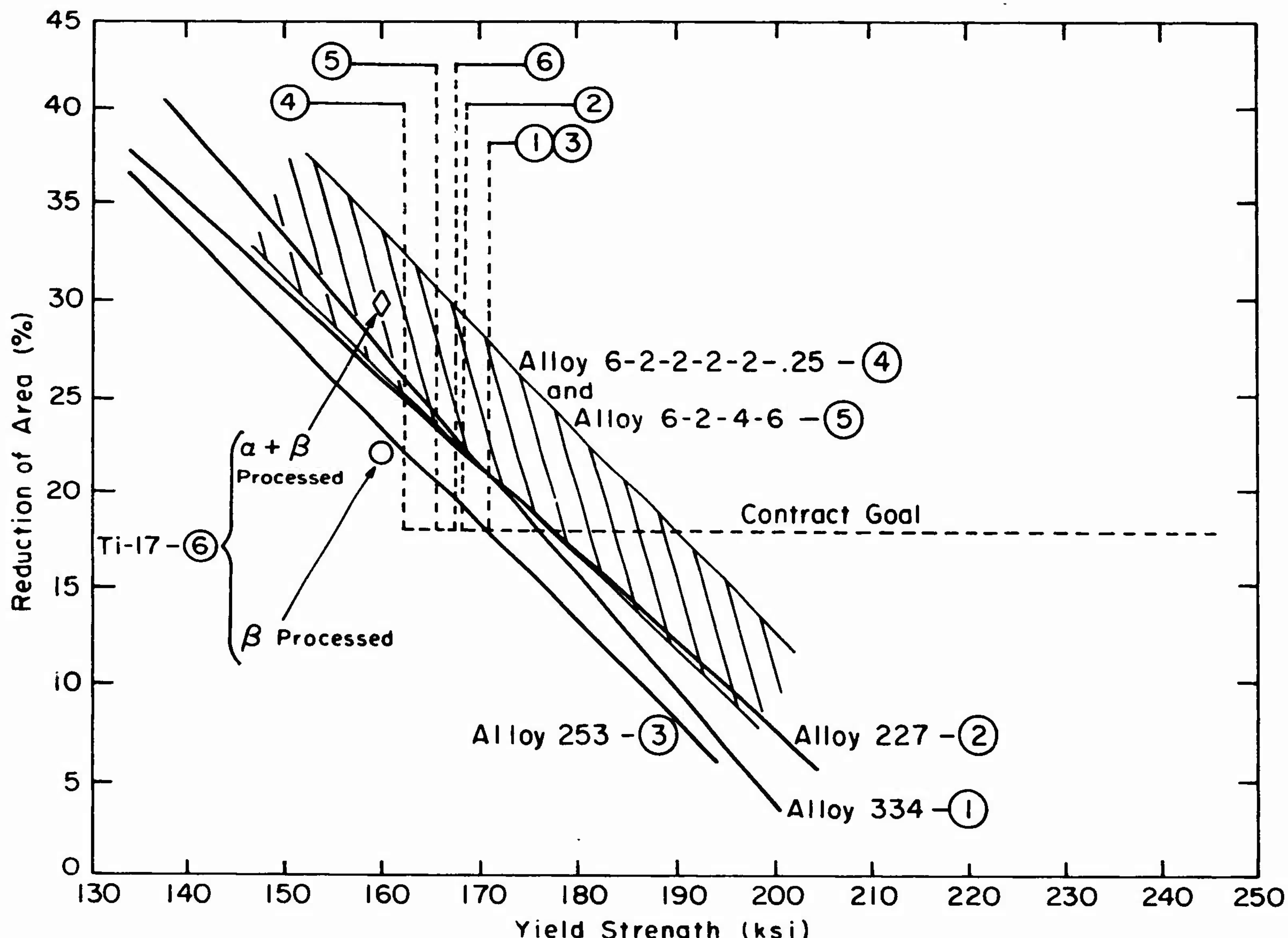


Figure 263 - Reduction of area-yield strength characteristic alloy trend lines for present contract alloys and experimental and semi-commercial deep hardenable alloys. Goal properties for each alloy are density normalized (number code above).

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